Chemical Engineering Progress

Chemical Engineering Progress

Volume 48
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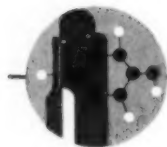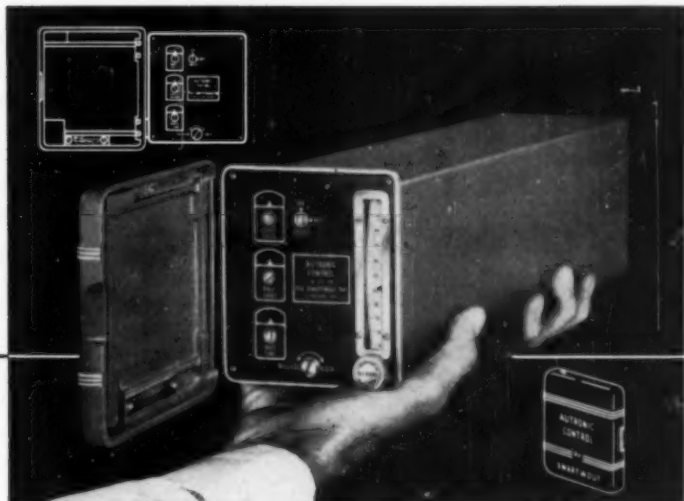
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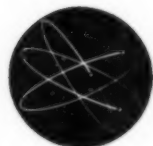
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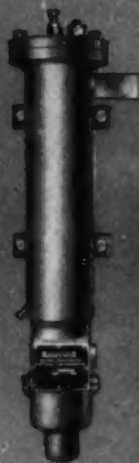
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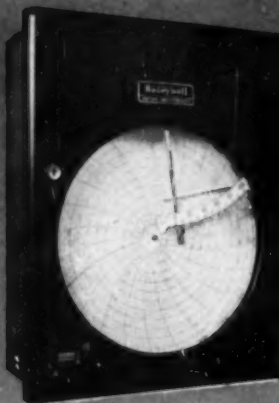
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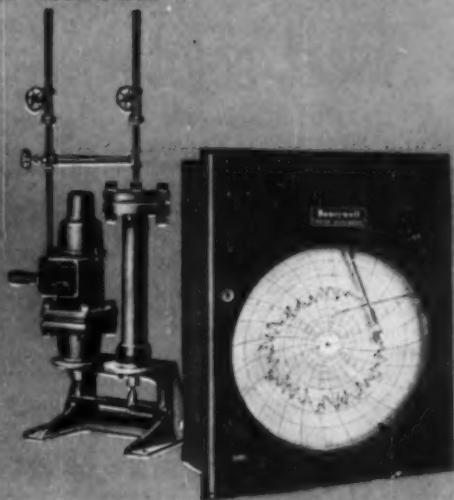
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OPINION AND COMMENT

NOW—VIRTUE FROM NECESSITY

A GATE watchman on a construction job observed a certain workman heading out the gate trundling a wheelbarrow filled with straw. Knowing that this particular man was light-fingered, the watchman suspected that something was hidden in that straw. So, he stopped the man with the wheelbarrow and searched assiduously through the straw. He found nothing, and finally, reluctantly allowed the workman to pass. He was vexed for he was sure something was crooked. A day or so later the same workman approached to pass out of the gate, again with a wheelbarrow filled with straw. This time the watchman said to himself, "Aha! He thinks he has lulled my suspicions. This time there really will be something hidden in the straw." So he searched, and again he failed to detect any thievery. Once more, reluctantly, he let the man pass. The same episode occurred every day or so for quite a while. Each time the watchman searched through the straw carefully but never was he able to find anything hidden.

About a year later, the watchman encountered the suspect thief and said, "Joe, tell me—on that job last year when I used to search the straw in your wheelbarrow—what in the world were you stealing?" The workman's reply: "Wheelbarrows."

This simple tale represents a phenomenon common wherever human beings are gathered. The thief was a good student of human nature, for we are inclined to forget the wheelbarrow when we see the straw.

Modern business is extremely complex, and we often make it more complicated than necessary by trying to dodge responsibility. How often we insist on sending and receiving copies of documents simply to keep our records clean! Perhaps it would be easier all around if sometimes we accepted a share of responsibility when things go wrong if only to help the other fellow, even when we aren't at fault. When the going is tough, the important thing isn't to place the blame, but to do what is best for our cause. Many a man whose job smothers him in paper work fails to think of the wheelbarrow under the straw. He concludes that too many papers flow his way and that he is persecuted. Often the correct analysis is that he doesn't organize his work well enough, and doesn't trust subordinates enough to pass work to them. Or, maybe what he really needs is training in rapid reading. Not many people know that it is often comparatively easy to triple reading speed, from 300 to 1000 words per minute, and that at the more rapid rate comprehension is vastly improved, not diminished as one might suspect.

Another way in which we are inclined to search the straw and miss the wheelbarrow is in criticizing subordinates for not seeming to want to accept responsibility. How often we fail to delegate the necessary authority!

One of the really common and really significant types of human failure is represented by a recent incident in which I participated. A young man asked my advice about changing jobs. He told me that he liked the job he had and was satisfied with the treatment he was receiving. He was working for a good employer and getting a salary quite satisfactory for the duties and responsibilities of his position; he had been offered a job at slightly higher salary, close to home and by taking it, would eliminate a long, rather difficult drive to. and from work every day. It naturally occurred to me to point out the possibility of moving his home closer to the job. The objection to this was financial. He had hunted for a house closer to the job but the houses there cost too much. He couldn't afford that change, so he said.

As our discussion proceeded it developed that my young friend was searching through the straw and overlooking the wheelbarrow. He was worrying about a long drive to and from work when all the while his real trouble was that he hadn't made progress in his profession in accord with his age and innate ability. If he had done so, housing problems would have given him no more trouble than they do other folks. I happened to know his employers thought highly of his ability and were trying to push him into more and more difficult and responsible tasks. They realized that he hadn't developed fast enough. He was actually willing to consider chucking aside an excellent situation with a first-class employer just to take a job nearer home with a company that couldn't possibly offer much opportunity for professional advancement. When he recognized the truth, he tackled the real problem which faced him. He's almost certain to succeed.

There is every indication that we are entering a period when engineers will be scarce in a sense unparalleled in any nation's history. Some believe it will be ten years before we can catch up. Now, as never before, there will likely be an opportunity for engineers to push ahead. No doubt a good many will miss the wheelbarrow under the straw and will go after "easier working conditions," or "better pay," or "more fringe benefits" without really thinking through to the possibility that these chimerical goals may represent no real advancement but only some temporary advantage. Only more responsibility and more authority, either technical or supervisory, can lead to real advancement, real professional progress.

Now, also, is the time for employers of engineers to work hard and intelligently to make sure that the engineers they have are being used to their fullest engineering capacity; that important engineering work carries the emoluments and prestige it deserves; and, that engineers capable of development not only have adequate opportunities to develop but also, in fact, get some needling to make them recognize the wheelbarrow under the straw.

Thus can we make great virtue from grim necessity.

W. T. NICHOLS,
Vice-President, A.I.Ch.E.

Maintenance

ITS ORGANIZATION AND OPERATION IN CHEMICAL PLANTS

LYMAN A. DARLING

Du Pont Company, Wilmington, Delaware

Covering the general theme of "Safeguarding What You Have," started in the December, 1951, issue with Safety, we go on this month to Maintenance, another factor in the preservation of property and plant. . . . Here below L. A. Darling, associated with the DuPont Co., discusses the functions of the maintenance department in a chemical company and the people concerned with maintenance. . . .

ALTHOUGH we in the chemical industry seem to be aware of the importance of maintenance to our business, the figures available do not give us a complete measure of its effects.

In the year 1948 the maintenance cost of a representative group of chemical companies was reported as roughly equal to half their profits. In the same year maintenance cost was equal to about 7 per cent of the gross property valuation of this group. These figures show the amount charged to maintenance, but they hardly tell the full story. They do not reveal the costs of inadequate maintenance and idle equipment, or yield losses and degraded product all results of improperly functioning equipment.

By any measure we use, maintenance is an important element of cost and it is our purpose here to discuss the organization of the people who are charged with the responsibility for maintaining the plants of the chemical industry.

In attempting to deal with the subject of maintenance organization and operation in the chemical industry one is immediately impressed by the variety of maintenance situations which exist in this industry. Chemical plants vary widely in product, process and size. Even when the plants are similar, the functions assigned to the maintenance department may vary widely in different plants.

Maintenance and People. But in all cases, the most important factor in the maintenance problem is people. The fundamental principles of organizing a group to do maintenance work do not appear to be especially different from those one would employ in organizing a group to do anything else. Yet in spite of this, progress in reducing maintenance cost and improving productivity of plants can be accomplished by improvements in the organization and operation of the maintenance group.

One basic principle of organizing a group is that the organization should fit the task. The task of a maintenance group is subject to wide variations, so the organization must be one which provides flexibility if it is to meet all the changes which occur in the maintenance assignment. This requirement of flexibility may have been so severe as to lead, in some cases, into thinking that a real organization is impractical. We believe this is a mistake, that there must be a well-defined organization if maintenance people are to do the best work of which they are capable.

The definition of the word organization contains some food for thought. It comes from one meaning of the word "organ," which is defined as "any part of an organism performing some definite function." An organism is "a living being," and the term organize has two meanings which seem to apply to our problem. One meaning is to "unite"; the other is to "bring into systematic relationship the parts of a whole."

This suggests that the effectiveness of an organization is determined by (1) how well each part performs its functions, and by (2) how well each part is coordinated with the other parts. It is our belief that we are on firm ground when we examine a proposed plan of organization from the standpoint of how much it will help each person to perform his assigned function, and how well it provides a means for coordination of the effort of the people who must work together.

Assuming the concept of an organization as a living thing, we know that in living things, if the function of one organ is impaired, the well-being of the whole organism is impaired. We know also that coordination between the parts of an organism is necessary for its survival. The analogy can be carried a step further. An organism must be able to adapt itself to changes in its environment if it is to flourish and be able to compete with other organisms which seek to supplant it.

Adaptability and Change. The need for flexibility arises from the need to meet unexpected situations and quick changes of plans. These arise from unexpected equipment failures, unexpected changes to production schedules and other causes. Something can be done about the causes of these unexpected changes, a matter to be touched on later. Whatever their cause, these quick changes in plans are a major problem to most maintenance organizations which should be recognized in formulating the organization structure.

If the organization is not sufficiently flexible each quick change becomes something of a crisis and some kind of emergency arrangement may be quickly
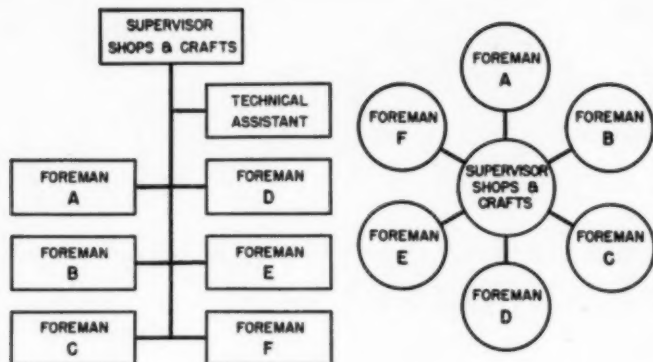
Fig. 1. Shops and crafts supervision.

set up to deal with the emergency. This change in organization leads to a series of readjustments in relationships which are likely to be made on the spot without benefit of thorough analysis.

It takes time for the members of a group to become familiar with all the relationships which a good organization must provide, and if these are constantly changing the members never know who is to do what. They are confused and to borrow one of their expressions ".hings are in an uproar."

In a well-conceived maintenance organization the objective of flexibility and coordination must be regarded as of primary importance. Success in achieving flexibility and coordination will be determined to a great extent by how well these basic requirements are provided. They are:

1. Adequate supervision.
2. Clear cut assignments of responsibility.
3. Individual interest and initiative.
4. Free flow of information.
5. Personnel training.
6. Planning and scheduling of work.
7. Adequate controls and records.
8. Technical assistance.

As stated previously, the situation in individual plants varies widely and therefore each plant must be treated as an individual case. We need some accurate information regarding the maintenance task and resources in the individual plant. These factors should be evaluated.

Factors which Influence Maintenance Organization

1. Functions assigned to maintenance department.
2. Physical arrangement of plant.
3. Equipment to be maintained.
4. Number of maintenance people.
5. Operating or production organization.
6. Process requirements.
7. Local customs and traditions.

This list isn't complete, but it will serve to illustrate the kind of information which is required. With this information in mind one can proceed with the analysis.

Determine Work-Load. The first step in the analysis is to determine the probable future work-load which the organization must bear. In an operating plant with adequate records, the recent

work-load and present backlog will be accurately known. For a new plant or a drastically changed condition in an operating plant, the work-load figures will be based upon the best available information. But, however it is obtained, everything should be based on the expected work-load, and all that follows is not likely to be better than this estimate.

Evaluating Requirements. The next step is to evaluate the supervisory requirements. The number of men a foreman can manage depends, among other things, upon what the men are doing and where they are working. If they are in one room doing standard operations he may be able to supervise 40 to 50. When they are in one room doing a variety of operations, as in a machine shop, he may not be able to do a good job with more than 25. If they are scattered widely over a plant, 12 or 15 pipe fitters will keep a foreman busy. A case comes to mind in which 36 pipe fitters with two foremen fell behind in their work steadily for six months. By making one of the fitters a foreman they caught up the lag in six months; 35 fitters and three foreman turned out appreciably more work than 36 fitters and two foremen.

The assignment of proper supervision at this, the first level, is worthy of the most careful analysis. Ingenuity may be needed to get the best supervision at the lowest cost. Sometimes combination gangs with two or more crafts working together as a team under one foreman will give better results than if the same men were assigned to individual craft foremen. Job standardization may be applicable and if so will materially reduce the supervisory load. Various other conditions such as job hazards, level of skill of mechanics, degree of coordination with others, etc., may influence the supervisory requirement, so each type of work should be studied individually. In an operating plant the performance of a group can be studied to determine the losses due to inadequate supervision, and this will usually indicate whether better supervision is justified.

Coordination of people and groups must exist between foremen and within the foreman's group. Much is said of the need for cooperation but more is needed than desire to cooperate. The means to do so must also exist, and many cases of failure to work in close harmony have been traced to the lack of proper basis for them to work together.

An important principle in obtaining cooperation is to place the responsibility and means at the lowest possible level. Men who work together should report to the same foreman. Foremen who

Lyman A. Darling is affiliated with the Du Pont Co. as division engineer of the mechanical, utilities and management engineering consultants, engineering service division. He joined Du Pont at the Old Hickory (Tenn.) plant as assistant power supervisor. From 1940-43 he directed operation of power facilities of the government operated by Du Pont's explosives department. Subsequently he was appointed works engineer at Hanford, but returned in 1945 to the engineering department in Wilmington as a special assistant in the industrial engineering division. In 1946 he became supervisor of power, water and maintenance section of the industrial engineering division. Early in his career he was affiliated with Commonwealth Edison Co., and the Texas Co.

work together should in so far as possible report to the same supervisor or engineer.

A typical problem of this sort is shown in Table A. Here are 95 men engaged in 19 different kinds of work, and 6 foremen. How do you arrange them to reduce the task of coordination to a minimum and give the men the best supervision? It is axiomatic that it is easier for a foreman to have coordination of individuals within his group than for several foremen to arrange it among men belonging to their separate groups.

The above arrangement as shown in Table A may not be an ideal one for various reasons. Foreman D may have a continuous problem to supply trucks and laborers for the riggers in Foreman B's group. Someone may think that the riggers should be assigned to Foreman D. But note that Foreman D now has 23 men widely scattered doing a variety of jobs, many of them small jobs and hard to schedule. It might be questioned if he could undertake the scheduling of the rigging for Foreman B. Also, who is responsible for the plant crane? Should it be Foreman D who runs the garage and trucks or Foreman B who is the only one who is allowed to use it?

A philosophical answer to a question of this kind is not at all reliable. Facts and figures are needed. A study of the number and type of contacts actually required in a period of time and then a comparison with the number and type which would have been required with an alternate arrangement, is an engineering approach and much more likely to be right.

During the course of this study it may be found that Foreman D is pinned down to his telephone too much of his time to dispatch trucks and laborers. Perhaps a dispatcher-clerk added to his force would release the foreman to supervise his men and thus increase their efficiency enough to pay the cost of the additional man.

Concerning the coordination of the activities of these six foremen, they all report to a single supervisor as shown in Figure 1. It matters a great deal which of these organizational patterns is used. Where the supervisor sits at the hub of the wheel and requires that everything pass through his hands a situation exists which will stifle the initiative and impair the flexibility of his organization.

The left-hand portion of Figure 1 shows a free flow of information and agreement between individual foremen. Compare it to the wheel where all the trivial and routine business overloads the supervisor and creates a bottleneck. He is so overloaded

Foreman A		Foreman B		Foreman C	
5	Carpenters	8	Millwrights	15	Machinists
3	Painters	3	Riggers	2	Blacksmiths
2	Sheet Metal	2	Welders	2	Tool Crib
4	Leadburners	2	Boilermakers		
1	Bricklayer				
15		15		19	

Foreman D		Foreman E		Foreman F	
2	Auto Mechanics	6	Electricians	12	Pipe-fitters
6	Truck Drivers	3	Instrument Mech.	2	Insulators
15	Laborers				
23		9		14	

that he can't even do a good job of coordinating, while the other things he should do get little or no attention.

The amount of cross flow between foremen is a good measure of the maturity and morale of an organization. It is a regenerative process because the more cross flow there is, the more skill the lower level acquires and the more confidence they acquire in their own ability to reach sound decisions by mutual agreement. The more they do this, the more they unburden their supervisor, giving him more time to see that they do work closely together and reach sound agreements. Psychological forces probably add the final touch to this arrangement because it produces a stronger sense of participation and responsibility in the foremen than the radial-bottleneck system. The difference in the atmosphere is felt by the men and an increased interest and initiative on their part may be expected.

With the unburdening of the supervisor, the opportunity is created for him to undertake improvements in the present situation. Opportunities for improvement always exist, are only waiting for someone to do something about

them. These may be opportunities to improve labor effectiveness, or supervision, to introduce new and better techniques, or to improve the equipment. With the supervisor giving thought to improvements, the chance to use technical assistance to good advantage will result. He will need assistance of fact-finders and analysts who are free to concentrate on this kind of work. These fact-finders may come from a central plant group or they can be assigned with full time to him.

The requirement of coordinating maintenance with plant operation can be a complex undertaking and will be a real thorn in the side of both production supervision and maintenance supervision if proper machinery does not exist to accomplish it. The provision for coordination of maintenance with operation is shown in Figure 2.

A heavy burden has been imposed on production supervision when it is required to deal with the different crafts involved in maintaining a modern chemical plant. When this arrangement is required, production people sometimes set up a supervisor on special assignment just to coordinate maintenance. A
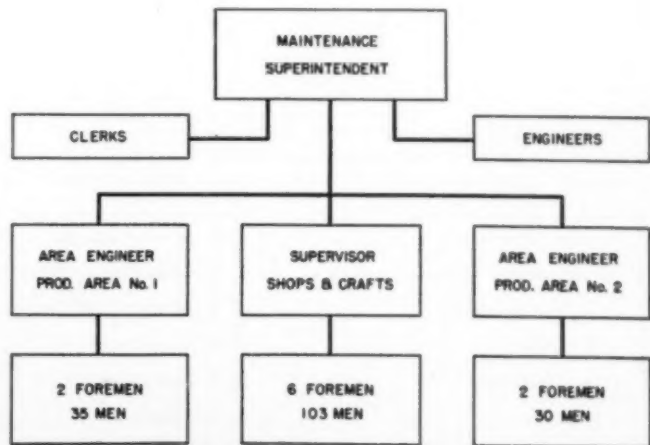
Fig. 2. Coordination of maintenance with operation.

better arrangement is to place this coordinator-supervisor in the maintenance organization. Here he is called maintenance area engineer.

Area Engineer. The most advantageous arrangement is usually one where the area maintenance unit covers a production unit. In this case one area engineer's responsibility covers the equipment and facilities of one production department head. It simplifies the maintenance contacts for the operating department head because there is normally only one maintenance man for him to contact. The area engineer has the responsibility of coordinating all maintenance work in the area, arranging for assistance from central shops and crafts when this is necessary.

Figure 3 shows the organization and personnel which might be found in an area group. Work which can be most economically performed by the central shops and craft should be requested of them. Much of the routine work in an area can be more efficiently handled by men assigned to the area than if the same men worked out of a central group. Most inspections, adjustments and minor repairs to production equipment are especially well done by an area group because of the high degree of this group's familiarity with equipment and process. Important advantages in coordination and in safety of personnel also accrue from this arrangement.

The composition of the area group will, of course, vary widely with the process, and that shown here is intended to illustrate a principle and not to fit any particular operation.

These area assignments should not be so large that the supervisor or engineer in charge cannot be well acquainted with his own men and the operating supervision of his area. He should also know the process and condition of all the buildings and equipment in his area. He should have sufficient personnel and tools to perform most of the routine maintenance and inspections in his area.

When he encounters a peak in his area he should be expected to call on the central shops and crafts for assistance. The area engineer will engage the central group in fabricating and major jobs of non-routine nature, including those which require workers with shops and craft skills and personnel which he does not have. The central shops and craft groups will usually handle construction and major alterations, except in the largest plants where a separate construction group may be justified. Advantages of this arrangement in providing flexibility to meet peaks in the areas are obvious.

Setting up planned routine assignments and preventive maintenance assignments for area mechanics markedly reduces the supervisory load. It has been found that a much greater part of the plant maintenance load can be handled as routine assignments than was once suspected. Relieving the supervisor of this burden gives him more time to investigate equipment failures and high cost maintenance items. It also gives him time to spend with his men in inspecting their work, heading off grievances before they become real complaints, and generally performing duties necessary to keep a crew interested and busy.

This area idea is adaptable to a wide range of operations and size of organization. The exception is the case of the smaller plant where the central group naturally enjoys all the advantages of proximity and short lines of communication with production people, which the area arrangement is intended to provide.

The area group should almost always have a small shop of its own. It should be located centrally in the area and should include a tool crib. The tool crib may also carry small stocks of most frequently used materials and supplies, such as bolts and nuts and packing. The area engineer's office with desks for his foremen can be located in the shop to advantage. This kind of arrangement will usually give better service to operation, at lower cost, than is possible with a strictly central group.

Everything possible should be done to shorten lines of communication and to establish close relationships which promote understanding, harmony and unity of purpose within the maintenance department and between maintenance people and production people.

Scheduled inspections and preventive maintenance will do much to minimize the number of unexpected equipment failures. Close working relationships with production people will tend to reduce the amount of unscheduled work which they request. Proper records can help maintenance people show their management the consequences of breaking into maintenance schedules with sudden unpredicted demands.

All that can be done to reduce the number of sudden changes should be done, but at best many of them are unpredictable. It has been proved many times that it costs two or three times as much to do a job on an emergency basis as on a normal basis. Our objective is to keep these sudden changes from becoming emergencies, with their attendant confusion and loss of efficiency. They will not be emergencies if plans can be revised quickly and accurately without creating confusion.

Who is in a better position to see what should be done than the man on the spot? If he has the authority to act, he can quickly reorient his forces to meet the new situation. If his lines of communication are short he can promptly advise all who will be affected by his sudden change of plans. This will reduce the time required for him to get the help he needs, provided those he asks can act promptly also. It will also reduce the damage to other schedules which his change of plans might cause.

Flexibility in an organization depends to a considerable degree upon delegation of authority down the line. Yet
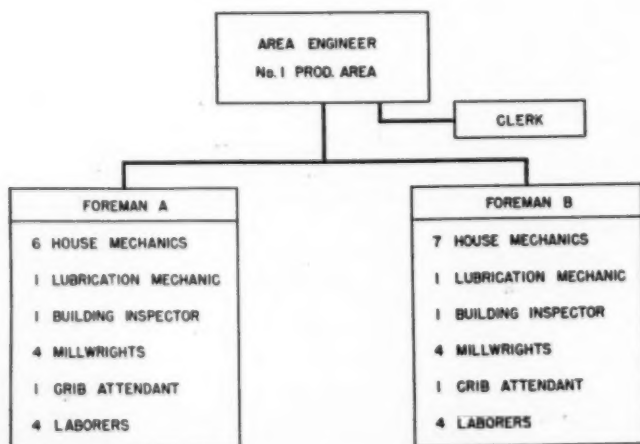
Fig. 3. Area maintenance group.

the degree to which authority can be safely delegated down the line depends upon the following:

Competence of supervision.
Short lines of communication.
Cooperation between supervision.
Clear definition of authority and responsibility.

The area setup described earlier definitely shortens lines of communication. It also tends to increase the interest of maintenance people in production problems and vice versa. It provides a natural boundary for responsibility and consequently for authority.

Maintenance—An Opportunity for the Future. The need for competent supervision has long been recognized but this author questions whether we in the chemical industry have done enough to provide the number and caliber of maintenance supervisors we will need in the years ahead. It takes a good engineering education, character and energy, an interest in maintenance, and years of experience to develop a good maintenance supervisor. What inducement is offered a talented young man to enter the maintenance field? What about a career in maintenance or one that is founded upon experience in maintenance? Will that attract some of the country's best young brains?

We have talked to a sufficient number of talented young maintenance engineers, and some not so young, with a resultant alarm at the prospect. *They point out that the record seems to indicate that a young man starting in maintenance can hardly aspire to reach a high place in industry.* One can point to some notable exceptions but cannot prove to them that their fears are groundless. Some of our best prospects for the future are seeking a way to get out of maintenance. This, too, in the face of a rapid increase in the mechanization of the chemical industry. Our equipment is becoming more complex and costly, our service conditions are becoming severer, and our maintenance costs rising. We have already reached a maintenance barrier at some points in our technological advance so it would seem prudent to take steps to attract and hold in maintenance a portion of our best talent.

To get back to the subject—the object in training supervision is to prepare for greater responsibilities. One way to accelerate this process is to give responsibility as fast as it can be taken.

Authority and Responsibility. Authority must go with responsibility if the assignment is to be meaningful. Both must be clearly defined and care taken by superiors not to infringe the assignments. We can all think of cases in which attempts to pass authority down

the line have come to nothing because a young supervisor's superiors snatched it away when he stumbled a bit in his new role. If delegation of responsibility down the line is to succeed it must be carefully defined and backed up by carefully defined authority.

Another matter of importance to the success of a maintenance organization is the adequacy of engineering and staff assistance available to them.

Engineering studies of maintenance problems offer one of the surest ways to reduce maintenance costs. The range of problems which may be studied profitably is as great as the range of maintenance work. Equipment failures, high cost maintenance items, work methods or practices, preventive maintenance schedules, tools and shop facilities, in fact almost anything in connection with maintenance is an opportunity for improvement and cost reduction. The well-known engineering approach has been proved to be as effective in maintenance cost reductions as in any other kind of cost reduction.

Technically trained supervisors are desirable in line supervision, but it is an error to expect them to make detailed engineering studies while they have heavy supervisory responsibilities. One or the other will surely suffer.

Engineers assigned specifically to study maintenance problems will pay their way several times over, and in addition these assignments offer an opportunity to train young engineers for the supervisory job of tomorrow.

The manner of welding these staff engineers into the organization is a matter of judgment and the local situation. When a sizable number is involved it may be better to put them in a central group under supervision of an experienced engineer who reports to the maintenance superintendent or head of the department.

A planning and scheduling specialist is usually a must in such a group. He can be of service in plant-wide scheduling to level out the plant work-load. He will also be of value in developing plans and schedules for major overhauls. A lubrication engineer is likely also to be a valuable member of this group. Other members of this group can do profitable work in analyzing high cost maintenance items, selection of better materials, investigation of premature failures, and similar types of fact-finding studies.

Material requirements usually can be handled to advantage by this group, especially when some investigation is required to determine the type which should be purchased. Other staff assistance may include study of preventive maintenance schedules and maintaining the drawings and engineering information file.

Conclusions

The best maintenance organization for a chemical plant will be one designed specifically to fit the individual plant. A careful analysis of facts and figures is necessary to define the maintenance task which the maintenance organization must fit. Such an analysis can be expected to reveal that flexibility must be built into the organization to accommodate the wide variations of work-load, and to give prompt service to operations.

Recognition must be given also to the increasing complexity and cost of chemical plant equipment. Maintenance difficulties are beginning to appear as barriers to progress and maintenance costs are rising. More talented young engineers must be attracted to careers in maintenance if we expect to deal effectively with this development.

Discussion

George Collins (Wallace Clark & Co., 521 Fifth Ave., New York, N. Y.): To what extent have you applied standards or incentives in connection with maintenance work for higher productivity?

L. A. Darling: Incentives have been applied to a somewhat limited extent. Standards are rather widely used and their use is increasing within our company. The standards are used more for accurate planning, for control of costs than for payment of incentive wage at this time.

George Collins: That would be more on a measured day work basis?

L. A. Darling: That is correct, that sort of thing.

T. Lincoln (Naugatuck Chemical Co., Naugatuck, Conn.): Would Mr. Darling elaborate on how the standards for such systems are developed?

L. A. Darling: Some of our standards are based on time study. Also, several new techniques, such as Methods-Time-Measurement, are being tried to a limited extent. In practically all cases the standards we use are based on some kind of measurement. The most widely used means of application is a breakdown of basic time elements which can be added together to give us the standard time on an individual maintenance job. That is to say, we put the elements together and synthetically get the standard time to do a complete job, such as installing a run of pipe from this side of the room to that side. Most of the effort in our company is now in the direction of getting accurate time elements for the small increments which compose the average maintenance job.

LIMITING FLOW AND HOLDUP IN A SPRAY EXTRACTION COLUMN[†]

G. W. MINARD and A. I. JOHNSON [‡]

University of Toronto, Toronto, Canada

A study of limiting flow and holdup was carried out in a 4.0-in. I.D. by 8-ft. spray tower of the Elgin design (5). The spray chamber of the column was 18 in. long by 8⅝ in. I.D., enclosing an entry cone 7 in. I.D. by 4 in. I.D. by 10 in. long. The spray nozzles were located 2 in. from the entry cone. The settling chamber was 12 in. long by 8⅝ in. I.D.; the continuous phase entered the column proper over a weir 4 in. I.D. by 4 in. long. The limiting flow condition was taken as the point of rejection of the drop mass from the entry cone and holdup was estimated either by observing the pressure differential across the column or by settling the dispersed phase in the column.

The variables studied include:

a. Characteristics of flat-plate nozzles with orifice diameters varying from 0.040 in. to 0.228 in.; with 97 to 21 orifices/nozzle.
b. Effect of specific gravity difference between phases with $\Delta\rho'$ varying from 0.595 to 0.1.
c. Effect of viscosity of continuous phase with η_c varying from 36 cps. to 0.9 cps.

The following equations are derived relating the flow rates of the two phases at flooding and holdup at flooding:

$$\left(C_c\rho_c V_c{}^n\right)^{\frac{1}{n+1}} + \left(C_D\rho_D V_D{}^n\right)^{\frac{1}{n+1}} = \left(\Delta Z\Delta\rho\right)^{\frac{1}{n+1}}$$

$$H_f = \left(\frac{C_D\rho_D V_D{}^n}{\Delta Z\Delta\rho}\right)^{\frac{1}{n+1}}$$

$$V_c = V_o - KH_f{}^{2/3}$$

Results from the tower are expressed graphically to show the usefulness of these equations and the following correlation based on the first equation above is proposed for limiting flow in a similar tower:

$$V_c{}^{\frac{1}{2}} = -N\eta_c{}^{-0.075} V_D{}^{\frac{1}{2}} + 47\eta_c{}^{-0.075}\Delta\rho^{-0.14}\rho'_c{}^{-0.50}$$

The limiting flow data were also correlated by the recent method of Elgin and Foust and the two correlations compared.

L IQUID-LIQUID extraction is that chemical engineering operation effecting the transfer of a solute between two liquid phases, the operation depending on the immiscibility and difference in density of the two phases. This is usually carried out by continuous countercurrent flow in vertical towers, the design of which involves two considerations: (1) the maximum throughput and (2) the extraction efficiency at the optimum flow condition. In practice these factors fix the diameter and height, respectively, of the tower to be used for a given application.

The simplest continuous countercurrent extraction tower is the spray tower.

This consists essentially of a vertical cylinder (Fig. 1) through which the two phases pass countercurrently, one as a continuum, the other as drops flowing in the opposite direction. The spray nozzle may be either at the top or bottom of the tower depending on the density of the dispersed phase. In either case the dispersed phase separates from the continuous phase at the end of the tower opposite the spray end and is withdrawn there. At this same end the continuous phase is introduced and it in turn is withdrawn at the spray end thus effecting countercurrent flow.

For a given continuous phase rate, as the dispersed phase rate is increased, the number of drops increases, the volume fraction of the column occupied by this dispersed phase is defined as the holdup H. Since holdup and drop size govern contact area, both enter into
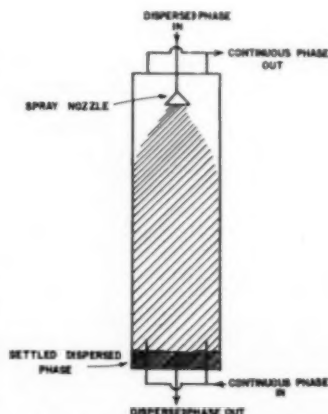
Fig. 1. Basic design of a spray extraction tower. Heavy phase dispersed.

the extraction efficiency of the tower. The limiting-flow condition corresponding to a given continuous phase rate (V_c) is that dispersed phase rate (V_D) at which not all the phase from the spray nozzle is permitted to pass through the tower. A study of this limiting condition is presented in this paper.

Several studies of extraction efficiencies for various systems in spray towers have been reported (1, 3, 5, 6, 8-11). However, the only attempts to analyze the limiting flow condition are those made by Elgin and Browning (6) and Elgin and Blanding (5); they propose two equations for the curve relating the two phase rates at flooding. As a further outcome of Elgin's work a significant change in spray column design was proposed in the use of enlarged spray and settling sections (Fig. 4); in this tower "flooding" is defined as the dispersed phase rate at which the drop mass just moved from the entry cone into the column proper.

The purpose of the present paper was to study further the problem of limiting-flow conditions in a spray tower of the design proposed by Elgin and Blanding. In this paper an attempt was made to establish a relation for limiting flow at "rejection" rather than at "flooding." The condition of rejection corresponds to the dispersed phase rate at which the drop mass overflows the entry cone; this condition is believed by the present

DROP PATTERN FOR HOLD-UP THEORY

MODIFIED BERTETTI THEORY
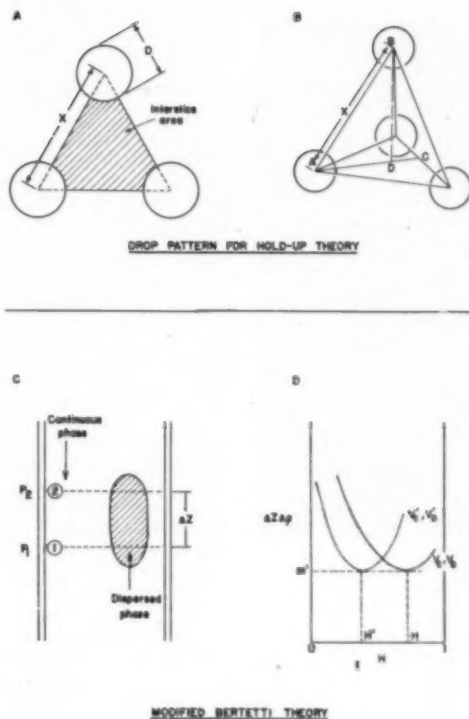
Fig. 2.
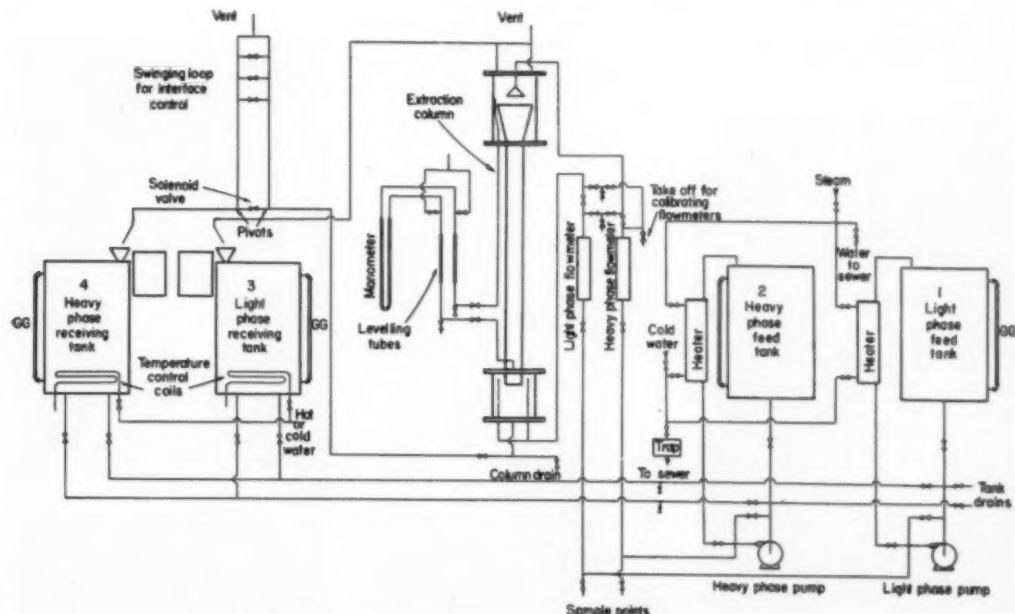
Fig. 3. Flow diagram for liquid-liquid extraction apparatus spray tower operation.
Heavy phase dispersed.
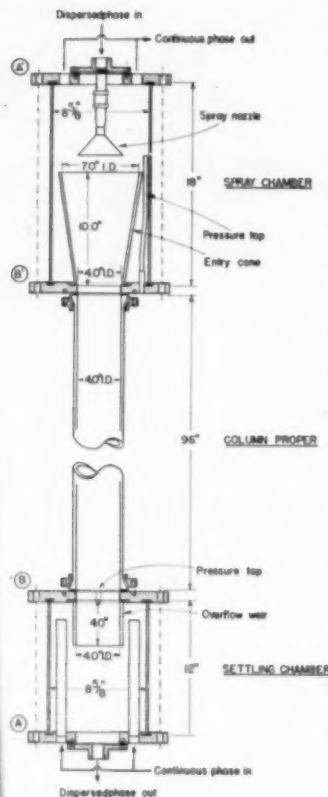
Fig. 4. Spray extraction column. Heavy phase dispersed.
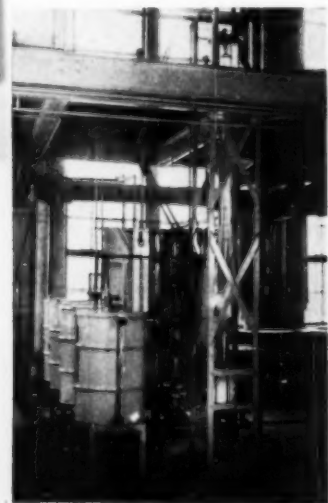
Fig. 5. Spray extraction column. Heavy phase dispersed.

authors to represent a true maximum throughput for the particular column and system.

Theoretical Considerations

Any analysis of two liquid-phase countercurrent flow is rendered extremely difficult by the large number of physical properties influencing the flow, by the difficulty of measuring some of these properties (notably drop size), by the complicated flow pattern, and by unknown factors arising from the design of the equipment. The theoretical approach used here is the assumption of a simplified flow pattern used to obtain (1) a relationship between holdup at flooding and rate of flow of continuous phase, and (2) a relationship between the two phase rates at flooding.

a. *Holdup at Flooding.* By assuming spherical drops of uniform diameter D equally spaced at a distance x, the flow pattern may be represented as in Figure 2(A) and (B). The interstice area through which continuous phase flows is

$$\frac{\sqrt{3}}{4}x^2 - \pi \frac{D^2}{8} \qquad (1)$$

and it is easily shown that for this pattern the holdup in terms of D and x is

$$H = \frac{\sqrt{2}\pi}{6}\left(\frac{D}{x}\right)^3 \qquad (2)$$

Flooding is now considered as the condition when the velocity of continuous phase through the interstices becomes equal to the static velocity, or velocity of a drop of dispersed phase through stationary continuous phase, that is, when

$$\frac{V_c \frac{\sqrt{3}}{4}x^2}{\frac{\sqrt{3}}{4}x^2 - \pi \frac{D^2}{8}} = V_o \qquad (3)$$

Substituting for D/x from (2) there is obtained finally

$$V_c = \left[1 - \frac{\pi}{2\sqrt{3}}\left(\frac{6}{\pi\sqrt{2}}\right)^{\frac{2}{3}} H^{\frac{2}{3}}\right] V_o \qquad (4)$$

or

$$V_c = V_o - KH_f^{\frac{2}{3}} \qquad (5)$$

where V_o and K are constants for a given pair of phases and a given drop size.

b. *Relationship Between Phase Rates at Flooding.* By an extension of the theory proposed by Bertetti (2) for gas-liquid flooding in packed towers a relationship between the phase rates at flooding may be derived. The flows of the two phases are represented dia-

grammatically in Figure 2(C). For the continuous phase the total energy at section (1) is less than that at section (2) by the friction loss f_c:

$$\frac{V_2^2}{2g} + \frac{p_2}{\rho_c} + Z_2 - f_c = \frac{V_1^2}{2g} + \frac{p_1}{\rho_c} + Z_1 \qquad (6)$$

Assuming equal velocity heads:

$$\frac{P_1}{\rho_c} - \frac{P_2}{\rho_c} = (Z_2 - Z_1) - f_c \qquad (7)$$

By a similar consideration of the dispersed phase

$$\frac{P_1}{\rho_D} - \frac{P_2}{\rho_D} = (Z_2 - Z_1) + f_D \qquad (8)$$

Since the pressures are equal in both phases at any section, it follows that:

$$\Delta Z \Delta \rho = \rho_D f_D + \rho_c f_c \qquad (9)$$

It is asserted that the fraction of the tower cross section through which dispersed phase is flowing is numerically equal to the holdup, H. Since V_c and V_D are flows in feet per hour based on the cross-sectional area of the tower (cu.ft.) /(hr.)(sq.ft.), the actual average velocity of the dispersed phase is (V_D/H) ft./hr., and of the continuous phase is $V_c/(1-H)$ ft./hr. It is also asserted that the friction or drag losses f_D and f_c vary as these velocities to powers n and n' respectively.
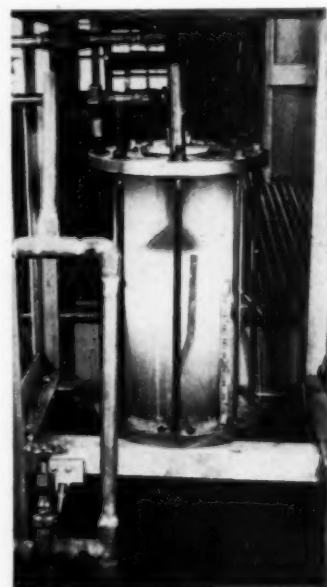
Fig. 6. Spray chamber.

Fig. 7. Settling chamber.

For laminar flow in each respective phase n or n' would be expected to be 1, and for high velocities where drag exceeds skin friction, n or n' would be expected to approach 2.

If C_D and C_C are proportionality constants Equation (9) becomes:

$$\Delta Z \Delta \rho = \rho_D C_D \left(\frac{V_D}{H} \right)^n + \rho_C C_C \left(\frac{V_C}{1-H} \right)^{n'}$$

(10)

In this relation ΔZ is a variable and for given values of V_D and V_C the left-hand term becomes a function of H which may be represented by a curve which passes through a minimum at m' as in the right-hand curve in Figure 2(D). For given values of V_D and V_C there is no solution for values of $\Delta Z \Delta \rho$ less than m'. This minimum value, m', must correspond to a limiting-flow state at which the holdup is H. For the same system and drop size but for different flows, V'_D and V'_C, this flooding condition would correspond to the same minimum, m', but a different holdup.

The exponents in this expression n and n' are determined by the character of flow in the two phases. Because of the complexity of such flow it is assumed for this discussion that it is the same in both phases and thus $n = n'$.

To find the minimum value of $\Delta Z \Delta \rho$ for a given value of V_D and V_C set;

$$\frac{d(\Delta Z \Delta \rho)}{dH} =$$

$$\frac{C_D \rho_D V_D^n}{H^{n+1}} - \frac{C_C \rho_C V_C^n}{(1-H)^{n+1}} = 0$$

(11)

from which

$$H = \frac{(C_D \rho_D V_D^n)^{\frac{1}{n+1}}}{(C_D \rho_D V_D^n)^{\frac{1}{n+1}} + (C_C \rho_C V_C^n)^{\frac{1}{n+1}}}$$

(12)

and

$$1 - H =$$

$$\frac{C_C \rho_C V_C^n{}^{\frac{1}{n+1}}}{(C_D \rho_D V_D^n)^{\frac{1}{n+1}} + (C_C \rho_C V_C^n)^{\frac{1}{n+1}}}$$

(13)

Eliminating H from Equation (10) using (12) and (13), and assuming $n = n'$ there is obtained:

$$(C_D \rho_D V_D^n)^{\frac{1}{n+1}} + (C_C \rho_C V_C^n)^{\frac{1}{n+1}}$$

$$= (\Delta Z \Delta \rho)^{\frac{1}{n+1}}$$

(14)
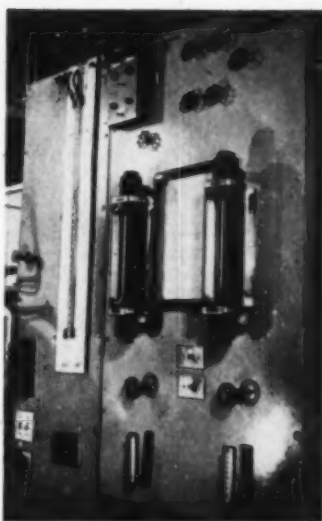
Fig. 8. Control panel.

Since C_C, ρ_C, C_D, ρ_D, ΔZ and $\Delta \rho$ are constant for a given system and drop size, the final equation may be written:

$$(V_C)^{\frac{n}{n+1}} = m(V_D)^{\frac{n}{n+1}} + b$$

(15)

Experimental work to substantiate the use of the equations above is presented.

A HEAVY PHASE DISPERSED   B   C LIGHT PHASE DISPERSED   D
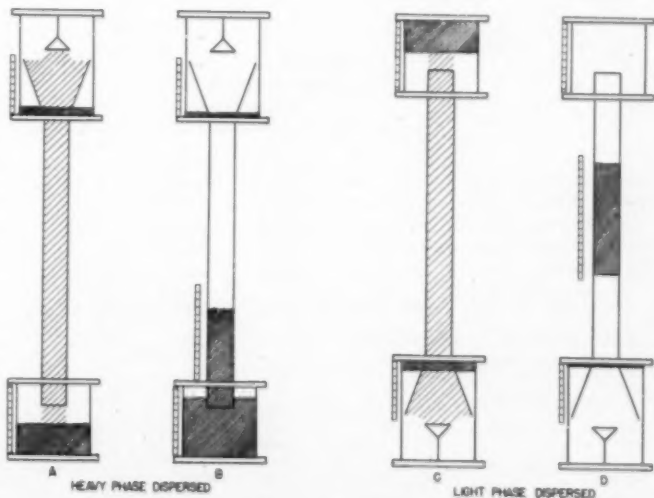
Fig. 9. Measurement of hold-up by settling.

TABLE 1

CHARACTERISTICS OF SPRAY NOZZLES

Nozzle	No. of Holes	Hole Diameter - Inches	Total Hole Area Square Inches
A	97	0.120	1.10
B	69	0.161	1.41
C	97	0.064	0.31
D	97	0.040	0.12
E	97	0.052	0.21
F	97	0.076	0.44
G	97	0.089	0.60
H	97	0.104	0.82
I	97	0.047	0.17
J	97	0.060	0.27
K	97	0.070	0.37
L	97	0.089	0.51
M	69	0.052	0.15
N	69	0.076	0.31
O	69	0.104	0.59
P	69	0.120	0.78
Q	21	0.064	0.067
R	21	0.076	0.095
S	21	0.104	0.18
T	21	0.120	0.23
U	21	0.161	0.43
V	21	0.191	0.60
W	21	0.228	0.86

Experimental Procedure

a. *Description of the Apparatus.* A flow diagram of the extraction column and the auxiliary equipment is shown in Figure 3. For limiting-flow determination the two phases were pumped from the two receiving tanks by the centrifugal pumps through the calibrated flowmeters to the column. For operation with the heavy phase dispersed, as indicated, the dispersed phase settling at the bottom of the tower was removed through the swinging loop, then returned to the heavy phase receiving tank; the light phase overflowed from the top of the tower to the light phase receiving tank. The two feed tanks were not used for the limiting flow-studies.

The extraction column, shown in detail in Figure 4, was made up of an 8-ft. length of 4.0-in. I.D. pyrex pipe as the column proper with a spray chamber 8½-in. I.D. by 18 in. long and a settling chamber 8½-in. I.D. by 12 in. long. These were connected

by nickel-plated cast-iron flanges as indicated. The column proper had tapered ends to accommodate standard Corning glass pipe flanges. The whole column was supported in a rigid angle iron frame.

The continuous phase was introduced into the annulus in the settling chamber between the outer cylinder and a projection of the column proper; the latter then acted as a circular weir admitting the continuous phase to the 4-in. pipe with a minimum of disturbance. In the spray chamber the velocity of the continuous phase was reduced gradually by means of the entry cone so that the entering dispersed phase, formed at the spray nozzle, met no sudden changes in velocity. The drops of dispersed phase settled out in the settling chamber, and the interface was maintained about 2 to 4 in. from the overflow weir by controlling the rate of removal of the dispersed phase.

Three-quarter inch streamline copper pipe was used throughout; the pumps (8 gal./min. max. capacity) were bronze-lined and the 45-gal. drums used as tanks had sheet copper linings. The two receiving tanks were equipped with copper coils to which hot or cold water was admitted through solenoid valves operated by thermostats in the tanks. The temperature of the two phases was thus maintained to within ±1° C.

The manometer connections for studying the pressure differential across the column are indicated in Figures 3 and 4. By means of air seals the pressure difference was transmitted to a manometer (containing water as indicating liquid) mounted on the control panel.

The spray nozzles were made of 16-oz. copper sheet soldered to a ¾-in. streamline-to-iron pipe adapter; the orifices were laid out on a square pitch and were drilled in the 4-in. diameter nozzle faces before the latter were soldered to the nozzle cone so that any roughness from drilling could be removed. Preliminary runs were carried out with nozzles made from 4-in. oil cans; these were less satisfactory because they corroded and because roughness around the orifices could not be removed from the inside surface.

The apparatus was designed for easy conversion to operation with the light phase dispersed. The same tanks and pumps were used for the light and heavy phases and the control loop operated in the same manner but in this case it permitted the continuous phase to leave while the dispersed phase settled out at the top and overflowed.

Figures 5-8, show details of the column and the control panel.

b. *Operating Procedure.* The continuous phase rate was set at the desired value and allowed to come to operation temperature (25° C.). The dispersed phase was then pumped to the tower at a rate well below flooding. When sufficient dispersed phase had settled out in the settling-chamber the valve in the exit line was opened and the swinging loop was adjusted so that the interface was maintained at the correct position. Since the head of dispersed phase in the swinging loop must be maintained equal to the head of continuous phase plus dispersed phase in the tower, the position of the swinging loop had to be adjusted constantly as the holdup in the tower increased.

At any setting of the dispersed phase rate about five minutes were required to obtain a steady pressure differential across the tower but the tower was allowed to operate at least ten minutes before a change was made to the next higher flow rate. Increments in dispersed phase rate were of the order of 3% of the expected flooding rate.

TABLE 2

CHARACTERISTICS OF LIQUID SYSTEMS STUDIED

SYSTEM	PHYSICAL PROPERTIES				
	Densities (25/25)		Viscosities (cps.)		Interfacial Tension (dynes/cm.)
	ρ_c	ρ_d	η_c	η_d	
1. Water into ethylene dichloride	1.249	1.000	0.765	0.893	27
2. Ethylene dichloride into water	1.000	1.249	0.893	0.765	27
3. Carbon tetrachloride into water	1.000	1.595	0.893	0.897	36
4. Ansco "C" solvent into water	1.000	0.825	0.893	0.572	36
5. V.M.& P. solvent into water	1.000	0.744	0.893	0.608	44
6. Carbon tetrachloride into glycerine solution No. 1	1.204	1.595	36.0	0.897	23
7. Carbon tetrachloride into glycerine solution No. 2	1.298	1.595	27.2	0.897	31
8. Carbon tetrachloride into glycerine solution No. 3	1.158	1.595	18.5	0.897	25
9. Carbon tetrachloride into glycerine solution No. 4	1.165	1.595	9.65	0.897	25
10. Solvent mixture No. 1 into water	1.000	1.439	0.893	0.867	39
11. Solvent mixture No. 2 into water	1.000	1.326	0.893	0.880	38
12. Solvent mixture No. 3 into water	1.000	1.090	0.893	0.901	39
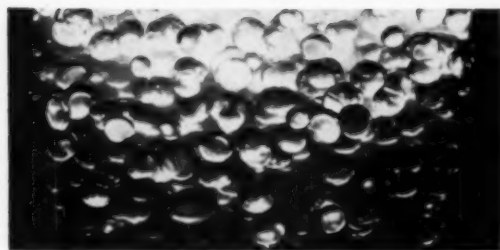
Fig. 10. Nozzle A: Solvent mixture No. 3 into water at rejection: $V_c = 350$ ft./hr., $V_o = 66$ ft./hr., $H_f = 0.22$.

Fig. 11. Nozzle D: Solvent mixture No. 3 into water at rejection: $V_c = 200$ ft./hr., $V_o = 33$ ft./hr., $H_f = 0.17$.

The Elgin flooding point was taken as the dispersed phase rate when the mass of drops in the column proper was observed to enter the entry cone. At slightly higher dispersed phase rates the mass of drops built up in the cone and eventually at "rejection" overflowed the cone into the annular space around the expander.

Operation with the light phase dispersed was similar to the above. The holdup or volume fraction of dispersed phase in the tower was estimated in two ways as follows:

1. By assuming that the pressure differ-

TABLE 3

LIMITING FLOWS AND HOLDUP AT REJECTION FROM ENTRY CONE

Using Nozzle F located 1-1/2 inches below entry cone. Holdup evaluated by method of settling. Room temperature unless otherwise stated.

SYSTEM	V_C cu.ft./hr/sq.ft.	V_D cu.ft./hr./sq.ft.	H
Ethylene dichloride into water	641	33	0.17
	568	43	0.18
	495	56	0.26
	472	63	0.27
	354	78	0.33
	285	85	0.33
	270	107	0.35
	155	150	0.41
Carbon tetrachloride into water	662	92	0.39
	568	113	0.31
	458	147	0.32
	353	179	0.37
	253	218	0.43
	155	258	0.47
V.M. & P. Solvent into water	627	58	0.23
	569	63	0.23
	494	74	0.26
	422	85	0.28
	353	100	0.33
	282	116	0.34
	218	139	0.40
	154	173	0.44
Amsco "C" solvent into water	627	36	0.19
	569	40	0.23
	494	47	0.25
	422	58	0.28
	353	72	0.30
	282	79	0.30
	218	87	0.36
	154	115	0.41
	89	144	0.48
Carbon tetrachloride into glycerine solution No. 1 (77°F.)	367	35	0.13
	258	50	0.21
	168	75	0.28
	87	135	0.38
Carbon tetrachloride into glycerine solution No. 2 (77°F.)	427	26	0.13
	298	44	0.17
	198	64	0.25
	139	96	0.34
Carbon tetrachloride into glycerine solution No. 3 (77°F.)	473	25	0.13
	399	30	0.14
	327	40	0.18
	259	73	0.24
	192	155	0.29
	128	168	0.35
Carbon tetrachloride into glycerine solution No. 4 (77°F.)	543	30	0.14
	465	35	0.15
	386	45	0.18
	307	64	0.22
	230	84	0.27
	162	127	0.32
Solvent Mixture No. 1 into water (77°F.)	500	127	0.23
	350	165	0.31
	200	233	0.38
	100	278	0.43
Solvent Mixture No. 2 into water (77°F.)	500	84	0.19
	350	111	0.25
	200	168	0.33
	100	239	0.41
Solvent Mixture No. 3 into water (77°F.)	500	26	0.13
	350	51	0.17
	200	83	0.25
	100	109	0.31

TABLE 4

PHASE FLOW DATA AT REJECTION FROM ENTRY CONE

System: Water - into - ethylene dichloride

NOZZLE	V_C cu.ft./hr./sq.ft.	$\sqrt{V_C}$	V_D cu.ft./hr./sq.ft.	$\sqrt{V_D}$
A	600	24.5	48	6.9
	534	23.1	66	8.1
	408	20.2	94	9.7
	338	18.4	118	10.9
	265	16.3	155	12.4
	222	14.9	175	13.2
	194	13.9	187	13.7
	125	11.2	237	15.4
	80	8.9	283	16.8
	50	7.1	340	18.4
D	565	23.8	27	5.2
	530	23.0	33	5.7
	462	21.5	34	5.8
	332	18.2	45	6.7
	230	15.2	75	8.7
	148	12.2	92	9.6
	105	10.2	107	10.3
	59	7.7	115	10.7
	23	4.8	126	11.2
F	646	25.4	34	5.8
	568	23.8	43	6.6
	500	22.4	52	7.2
	436	20.9	62	7.9
	375	19.4	74	8.6
	313	17.7	91	9.5
	253	15.9	110	10.5
	193	13.9	130	11.4
	136	11.7	170	13.0
	79	8.9	210	14.5
G	633	25.2	36	6.0
	568	23.8	42	6.5
	500	22.4	55	7.4
	436	20.9	72	8.5
	375	19.3	80	9.0
	313	17.7	97	9.9
	253	15.9	116	10.8
	193	13.9	148	12.2
	136	11.7	182	13.5
	79	8.9	248	15.7
H	633	25.2	36	6.0
	568	23.8	52	7.2
	500	22.4	68	8.3
	436	20.9	83	9.1
	375	19.3	103	10.1
	313	17.7	123	11.1
	253	15.9	144	12.0
	193	13.9	173	13.2
	136	11.7	203	14.2
	79	8.9	254	15.9
J	617	24.8	35	5.9
	552	23.5	35	5.9
	453	21.3	53	7.3
	358	18.9	68	8.3
	266	16.3	83	9.1
	178	13.4	125	11.2

Fig. 12. Nozzle F: Solvent mixture No. 2 into water at rejection:
$V_c = 500$ ft./hr., $V_o = 84$ ft./hr., $H_f = 0.20$.

Fig. 13. Nozzle W: Solvent mixture No. 3 into water at rejection:
$V_c = 100$ ft./hr., $V_o = 194$ ft./hr., $H_f = 0.38$.

ential was due entirely to the holdup of dispersed phase; this permitted instantaneous measurements of holdup during approach to flooding.

2. By settling out the dispersed phase in the tower after rejection had been reached and measuring its volume. This method, illustrated diagrammatically in Figure 9, involved measurements of the volumes of dispersed phase in the settling chamber and in the annulus around the entry cone before and after settling.

Comment on Result

a. *General.* Operation of the tower up to rejection without coalescence was possible in all the runs but three; these were with glycerine solution as continu-

TABLE 5

SPRAY TOWER OPERATION: WATER INTO ETHYLENE DICHLORIDE

COMPARISON OF LIMITING FLOW EQUATIONS EXPRESSING REJECTION FROM

ENTRY CONE

Nozzle	V_D Intercept	Slope	Equation
A	528	-1.54	$\sqrt{V_C} = -1.54 \ (\sqrt{V_D} + 35.4$
B	545	-1.53	$\sqrt{V_C} = -1.53 \ (\sqrt{V_D} + 35.7$
C	305	-2.10	$\sqrt{V_C} = -2.10 \ \sqrt{V_D} + 36.7$
D	190	-2.82	$\sqrt{V_C} = -2.82 \ \sqrt{V_D} + 38.9$
E	272	-2.10	$\sqrt{V_C} = -2.10 \ \sqrt{V_D} + 36.6$
F	356	-1.93	$\sqrt{V_C} = -1.93 \ \sqrt{V_D} + 36.4$
G	441	-1.62	$\sqrt{V_C} = -1.62 \ \sqrt{V_D} + 36.0$
H	437	-1.77	$\sqrt{V_C} = -1.77 \ \sqrt{V_D} + 37.0$
I	257	-2.20	$\sqrt{V_C} = -2.20 \ \sqrt{V_D} + 35.2$
J	293	-2.15	$\sqrt{V_C} = -2.15 \ \sqrt{V_D} + 36.8$
K	345	-2.15	$\sqrt{V_C} = -2.15 \ \sqrt{V_D} + 39.9$
L	370	-2.05	$\sqrt{V_C} = -2.05 \ \sqrt{V_D} + 39.4$
M	378	-1.59	$\sqrt{V_C} = -1.59 \ \sqrt{V_D} + 30.9$
N	360	-1.95	$\sqrt{V_C} = -1.95 \ \sqrt{V_D} + 37.0$
O	427	-1.82	$\sqrt{V_C} = -1.82 \ \sqrt{V_D} + 37.6$
P	470	-1.69	$\sqrt{V_C} = -1.69 \ \sqrt{V_D} + 36.6$
Q	351	-1.77	$\sqrt{V_C} = -1.77 \ \sqrt{V_D} + 33.2$
R	425	-1.58	$\sqrt{V_C} = -1.58 \ \sqrt{V_D} + 32.6$
S	430	-1.62	$\sqrt{V_C} = -1.62 \ \sqrt{V_D} + 33.2$
T	450	-1.60	$\sqrt{V_C} = -1.60 \ \sqrt{V_D} + 33.9$
U	475	-1.55	$\sqrt{V_C} = -1.55 \ \sqrt{V_D} + 33.8$
V	520	-1.47	$\sqrt{V_C} = -1.47 \ \sqrt{V_D} + 33.7$
W	516	-1.50	$\sqrt{V_C} = -1.50 \ \sqrt{V_D} + 34.0$

TABLE 6

CHANGE OF HOLDUP WITH APPROACH TO FLOODING

SYSTEM I

ETHYLENE DICHLORIDE INTO WATER

(Holdup calculated from pressure drop)

* Elgin Flooding.
Last value in each set corresponds to rejection.

Nozzle	V_C	V_D	Pressure Drop (In. water)	H	
A	625	22	4/8	0.02	
		35	7/8	.03	
		48	1 1/8	.04	
		62	2 1/8	.07	*
		65	5 1/8	.18	
	494	35	6/8	.03	
		48	1 2/8	.04	
		55	1 4/8	.05	
		62	2	.07	*
		68	3 7/8	.14	
		72	5 4/8	.19	
	387	35	6/8	.03	
		48	1 2/8	.04	
		62	1 7/8	.07	
		68	2 2/8	.09	
		75	2 5/8	.09	
		81	3 1/8	.11	
		86	3 4/8	.12	
		88	3 7/8	.14	
		92	5 4/8	.19	*
		95	6 3/8	.22	
		99	6 7/8	.24	
	285	35	5/8	.02	
		48	1 1/8	.04	
		62	1 3/8	.05	
		75	2 1/8	.07	
		88	3 2/8	.11	
		95	3 4/8	.12	
		107	3 6/8	.13	
		109	4 6/8	.17	
		115	5 3/8	.19	
		120	7	.24	
		123	7 7/8	.27	
	187	35	5/8	.02	
		55	1	.04	
		75	1 5/8	.06	
		95	2 5/8	.09	
		115	3 5/8	.13	
		129	4 2/8	.15	
		144	5 1/8	.18	
		151	6 1/8	.21	
		158	7 5/8	.27	*
		167	8 6/8	.30	
		169	9 2/8	.32	
	91	35	5/8	.02	
		62	1	.04	
		88	1 6/8	.06	
		135	2 6/8	.10	
		144	3 7/8	.14	
		172	4 4/8	.16	
		188	6	.21	
		203	7	.24	
		218	8 3/8	.29	
		225	9 2/8	.32	*
		233	10 6/8	.37	
		240	11 1/8	.39	
		246	12	.42	
	0	51	1	.04	
		104	2 4/8	.09	
		166	4 4/8	.16	
		194	5 7/8	.21	
		222	7	.24	
		266	14 4/8	.50	
		282	14 6/8	.51	

ous phase. Observation of the rejection was easier than Elgin flooding, and the higher holdup and greater agitation through the tower at this state should result in higher extraction coefficients as well as a slightly greater total throughput.

Because of limited pump capacity, it was not possible to operate the apparatus at a continuous phase rate high enough to prevent dispersed phase from entering the column proper. On the other hand operation at zero continuous phase rate was usually not satisfactory because at the high velocities of dispersed phase through the nozzles used large numbers of fine drops were formed. Where the systems and nozzles were such that this atomization was not obtained, both Elgin flooding and rejection could be observed at zero continuous phase rate.

As discussed previously, the swinging loop required constant attention to maintain the correct interface position. An attempt was made to use a solenoid valve by-passing the swinging loop and operated by electrodes at the interface. This gave good, automatic control but the resulting surging interfered with the pressure differential measurements and this method was abandoned.

Preliminary studies indicated that the best nozzle location was about 2 in. outside the entry cone; locating the nozzle inside the cone caused coalescence probably as a result of the direct impingement of the streams of dispersed phase from the nozzle on the drop mass building up in the entry cone. Location outside the cone also permitted observing and photographing drop formation.

b. *Effect of Nozzle Characteristics.* Characteristics of the 23 flat-plate nozzles used in this investigation are given in Table 1. Physical properties of the 12 different liquid systems used with these nozzles are given in Table 2.

Observations at rejection for nozzle F for some of the systems are exemplified by the data in Table 3. In these the rejection observations for the system water dispersed into ethylene dichloride indicated that this limiting condition could be represented as straight lines if values of $V_C^{1/2}$ were plotted against values of $V_D^{1/2}$. This permitted writing equations in terms of $V_C^{1/2}$ and $V_D^{1/2}$, using the slopes and intercepts of the graphs of the experimental results such as are given in Figure 14. For this system the limiting flow data for two of the nozzles, A and D, plotted in Figure 14 are given in Table 4, and typical limiting-flow equations are given in Table 5. All data when plotted as $V_C^{1/2}$ vs. $V_D^{1/2}$ give straight lines for engineering purposes and indicate that the value of n in Equation (15) should be unity.

Fig. 14.

SPRAY TOWER - WATER INTO ETHYLENE DICHLORIDE

REJECTION FROM ENTRY CONE

Room temperature 20–30°C

97 holed nozzles:

Nozzle	Orifice diam.	
A	0.120"	◇
D	0.040	△
F	0.076	⬓
G	0.089	✕
H	0.104	●
J	0.059	▲

NOZZLE A 97 - 0.120"

TABLE 7

DEVELOPMENT OF A CORRELATION FOR LIMITING FLOW IN A 4" SPRAY TOWER

SYSTEM	EQUATION OF LIMITING FLOW CURVE	D_p (in.)	$\Delta \phi^1$	$f_C^{0.5}$	$f_C^{0.5}$	$\frac{f_C^{0.5}}{47.5 \mu_C^{0.1L}}$	$\frac{\rho_C'}{\rho_D'}$	$a\left(\frac{\rho_C'}{\rho_D'}\right)^{0.5}$	.056 D_p	$\frac{f_C^{0.5}}{1.80\, D_p^{-0.058}}$
1.	$\overline{V}_C = -4.54\,\overline{V}_D + 35.6$		0.369	1.12	39.6	1.01	1.849	-1.72		
2.	$\overline{V}_C = -1.74\,\overline{V}_D + 36.4$	0.22	0.369	1.00	36.4	0.93	0.900	-1.56	0.919	0.80
3.	$\overline{V}_C = -1.64\,\overline{V}_D + 43.1$		0.595	1.00	43.1	0.97	0.627	-1.30		
4.	$\overline{V}_C = -0.82\,\overline{V}_D + 39.4$	0.33	0.175	1.30	39.4	1.26	1.210	-2.22	0.940	1.16
5.	$\overline{V}_C = -1.99\,\overline{V}_D + 42.3$	0.27	0.256	1.00	42.3	1.08	1.360	-2.30	0.970	1.19
6.	$\overline{V}_C = -1.57\,\overline{V}_D + 79.3$	0.23	0.391	1.10	32.2	0.77	0.755	-1.37	0.921	0.70
9.	$\overline{V}_C = -1.99\,\overline{V}_D + 33.9$	0.21	0.430	1.08	36.7	0.87	0.730	-1.44	0.916	0.73
10.	$\overline{V}_C = -2.00\,\overline{V}_D + 45.7$	0.21	0.439	1.00	45.7	1.08	0.695	-1.67	0.916	0.85
11.	$\overline{V}_C = -1.57\,\overline{V}_D + 43.5$	0.21	0.326	1.00	43.5	1.07	0.751	-1.80	0.916	0.90
12.	$\overline{V}_C = -2.26\,\overline{V}_D + 35.4$	0.36	0.090	1.00	35.4	1.04	0.916	-2.07	0.951	1.06

NOZZLE D 97 - 0.220"

TABLE 8

DEVELOPMENT OF A CORRELATION FOR LIMITING FLOW IN A 4" SPRAY TOWER

SYSTEM	EQUATION OF LIMITING FLOW CURVE	D_p (in.)	$\Delta \phi^1$	$f_C^{0.5}$	$f_C^{0.5}$	$\frac{f_C^{0.5}}{47.5 \mu_C^{0.1L}}$	$\frac{\rho_C'}{\rho_D'}$	$a\left(\frac{\rho_C'}{\rho_D'}\right)^{0.5}$	.056 D_p	$\frac{f_C^{0.5}}{1.80\, D_p^{-0.058}}$
1.	$\overline{V}_C = -1.90\,\overline{V}_D + 38.0$	0.33	0.369	1.12	38.0	0.97	1.849	-1.67		
2.	$\overline{V}_C = -1.68\,\overline{V}_D + 36.7$	0.92	0.369	1.00	36.7	0.94	0.900	-1.50		
3.	$\overline{V}_C = -1.82\,\overline{V}_D + 43.5$		0.595	1.00	43.5	1.03	0.627	-1.41		
4.	$\overline{V}_C = -1.53\,\overline{V}_D + 38.8$	0.33	0.175	1.00	38.8	0.99	1.210	-1.68		
5.	$\overline{V}_C = -1.64\,\overline{V}_D + 41.1$	0.36	0.256	1.00	41.1	1.05	1.360	-1.90	.844	1.00
6.	$\overline{V}_C = -1.61\,\overline{V}_D + 31.0$	0.23	0.391	1.10	31.0	0.82	0.755	-1.40	.901	0.72
7.	$\overline{V}_C = -1.79\,\overline{V}_D + 33.4$	0.14	0.397	1.09	36.4	0.87	0.751	-1.55	.912	0.79
9.	$\overline{V}_C = -1.64\,\overline{V}_D + 36.0$	0.23	0.430	1.00	36.0	0.89	0.730	-1.43		
10.	$\overline{V}_C = -2.01\,\overline{V}_D + 47.4$	0.27	0.439	1.00	47.4	1.12	0.695	-1.68	.918	0.86
11.	$\overline{V}_C = -1.99\,\overline{V}_D + 45.4$	0.25	0.326	1.00	45.4	1.12	0.753	-1.76	.926	0.90
12.	$\overline{V}_C = -1.89\,\overline{V}_D + 36.5$	0.49	0.100	1.00	36.5	1.06	0.909	-1.80	.951	0.96
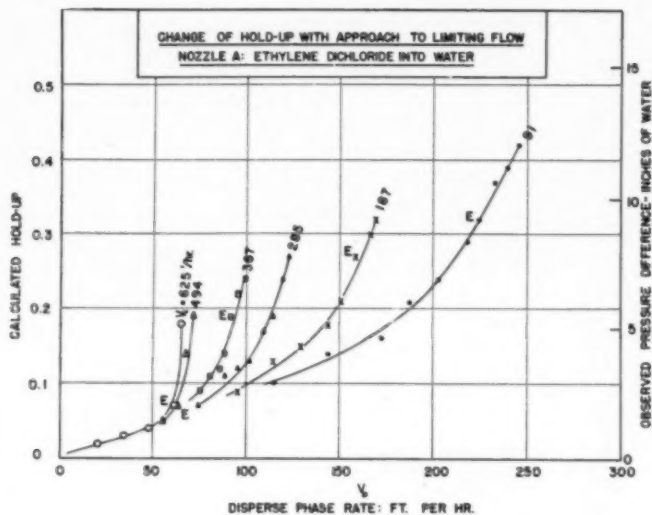
Fig. 15.

c. *Pressure Differential and Holdup*. In the calculation of holdup from pressure difference it is assumed that the wall friction is negligible. This is confirmed by both the observed and calculated pressure drop through the tower at maximum continuous phase flow with no dispersed phase present. By consider-

Fig. 16.

ing the average density of the column contents the relationship between holdup and pressure difference is readily shown to be

$$H_{calc.} = 0.00866 \frac{\Delta p'}{\Delta G} \qquad (16)$$

This method of calculating holdup was used for the runs involving the four different glycerine solutions, the three different solvent mixtures, and the system ethylene dichloride dispersed into water. The method of settling previously described was used to evaluate holdup for the three other systems studied. As a check the holdup in the system ethylene dichloride into water was also run by this latter method.

Results of Table 6 from which Figure 15 for the system ethylene dichloride into water (Nozzle A) were taken, show that there is not a sudden increase in pressure differential (i.e., in holdup) at either Elgin flooding or rejection. For high continuous phase rate, however, the curves are quite steep. As the continuous phase rate decreases, both flooding and rejection occur at higher holdups.

d. *Representation of Hold-up Data*. Two methods of representing hold-up data graphically were suggested by the theoretical considerations. The first, Equation (5), suggested that V_C plotted against $H^{\frac{2}{3}}$ would result in straight lines and this was found to be generally the case, for example for the system: Amsco "C" into water shown in Figure 16, the horizontal scale has been modified so that H may be read directly. This system was chosen because a value of the static velocity for a drop 0.224 in. in diam. was known (4); this size corresponds to the average drop size produced by nozzle F and it is seen that a straight line through the experimental points meets the V_C axis at this value satisfactorily. The best straight lines through the other points appear to be parallel corresponding to values of static velocity for larger and smaller drops.

This graph confirms the usefulness of using simplified flow patterns and suggests a method of correlating hold-up data.

The other method of plotting was suggested by Equations (12) and (13) which indicate that H plotted against V_D and $(1-H)$ plotted against V_C both on log-log plots should give a straight line; Figure 17 indicates that this appears to be so and this method is suggested for interpolating and extrapolating data. The observation that the slopes of the two plots are appreciably different indicates a limitation perhaps in the assumption made in arriving at Equation (15) that $n = n'$.
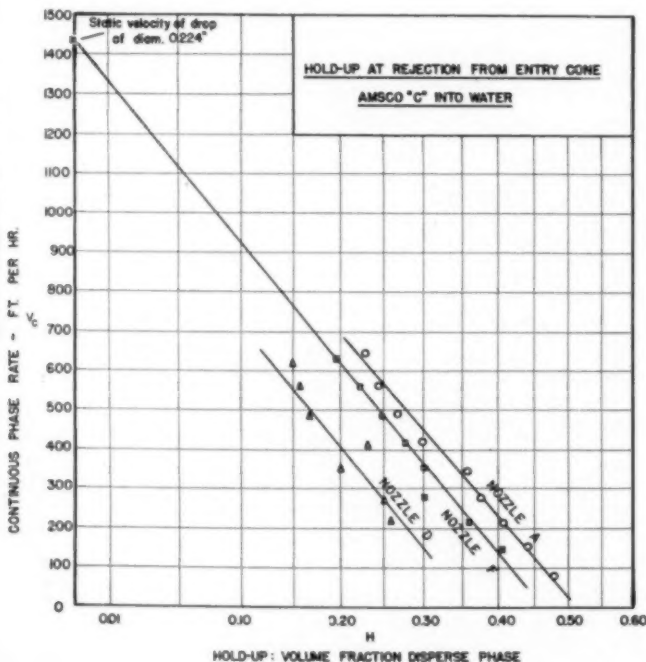
e. *Drop Size.* Drop size was estimated from photographs of the column proper enlarged approximately one and one-half times actual size; in each photograph between 20 and 50 drops were measured (to 1/32 in.) then averaged arithmetically. Figures 10-13 are typical photographs showing the drop size and uniformity; in general larger diameter orifices produced less uniform drops but even with small drops actual measurement discloses a large range in diameter.

(f) *Proposed Correlation.* Results of approximately 100 runs indicated that the value of n in Equation (15) is unity or that this equation may be written

$$V_C{}^{\frac{1}{2}} = -\left(\frac{C_D\rho_D}{C_c\rho_C}\right)^{\frac{1}{2}} V_D{}^{\frac{1}{2}} + \left(\frac{\Delta Z\Delta\rho}{C_c\rho_C}\right)^{\frac{1}{2}}$$
$$\underset{\text{Slope}}{} \qquad \underset{\text{Intercept}}{}$$

(17)

This is an improvement over Elgin's original derivation in that a slope is introduced into an equation which still indicates that $V_C{}^{\frac{1}{2}}$ may be plotted against $V_D{}^{\frac{1}{2}}$ to give straight lines. The terms shown include, theoretically, all the physical properties of the two phases and also drop size, while holdup at limiting flow was included in the derivation. The correlation proposed is based upon obtaining an empirical relationship for the slope and intercept terms. It should be noted that specific gravity (ρ') and viscosity in centipoises (η) are used in place of density and viscosity in engineering units in the following derivation:

1. *The Intercept Term.* Factors having most effect on this term appear to be the specific gravity difference $\Delta\rho'$ and the viscosity of the continuous phase η_c (cps) of which C_c is expected to be a function. That drop size has no appreciable effect was indicated by the constancy of the intercept term for the 23 nozzles tried for the system water-into-ethylene dichloride (*See* Table 5). The density of the continuous phase would be expected to be a factor and is considered in accordance with the above derivations. Actually the values of the density of the continuous phase were too nearly equal to unity and the observations not sufficiently sensitive to justify the latter treatment. Therefore, it is asserted that the intercept

$$b = f\frac{(\eta_c), f(\Delta\rho')}{\rho'_c{}^{\frac{1}{2}}}$$

(18)

Figure 18 shows $\rho'_c{}^{\frac{1}{2}}b$ plotted against $\Delta\rho'$ for constant η_c (that is, for water as continuous phase). Values of these variables for two of the nozzles are tabulated in Tables 7 and 8. From the slope of the line and the ordinate at $\Delta\rho' = 1.0$

$$\rho'_c{}^{\frac{1}{2}}b = 47.5\Delta\rho^{0.34}f(\eta_c)$$

(19)

Values of $\rho'_c{}^{\frac{1}{2}}b/47.5\Delta\rho^{0.34}$ for two of the nozzles are listed in Tables 7 and 8 and are plotted against values of η_c in Figure 18(B). Again the best straight line was drawn through the points and from the

slope and the value of the ordinate at $\eta_c = 1.0$

$$\frac{\rho'_c{}^{\frac{1}{2}}b}{47.5\Delta\rho^{0.34}} = 0.99\eta_c{}^{-0.030}$$

(20)

whence

$$b = 47\eta_c{}^{-0.030}\Delta\rho^{0.34}\rho'_c{}^{-0.50}$$

(21)

2. *Slope Term.* The above theory states that the slope varies as $(\rho'_D/\rho'_c)^{\frac{1}{2}}$. As with the intercept term the observations were not sufficiently sensitive to justify this but for want of a better treatment the two gravities were included accordingly. Examination of the data indicates that the slope is a function of drop size and viscosity of the continuous phase; it is therefore asserted:

$$m = \left(\frac{P'D}{P'C}\right)^{\frac{1}{2}} f(D_p)f(\eta_c)$$

(22)

Keeping η_c constant (water as continuous phase), $m(\rho'_c/\rho'_D)^{\frac{1}{2}}$ was plotted against D_p in Figure 19 (A). From the slope and ordinate at $D_p = 1.0$

$$m\left(\frac{\rho'_c}{\rho'_D}\right)^{\frac{1}{2}} = -1.80 D_p{}^{0.600}$$

(23)

then from a plot of

$$\frac{-m\left(\frac{\rho'_c}{\rho'_D}\right)^{\frac{1}{2}}}{1.80 D_p{}^{0.600}} \text{ vs. } \eta_c \qquad (\text{Fig. } 19B):$$

$$\frac{-m\left(\frac{\rho'_c}{\rho'_D}\right)^{\frac{1}{2}}}{1.80 D_p{}^{0.600}} = \eta_c{}^{-0.075}$$

(24)

whence

$$m = -1.80 D_p{}^{0.600}\eta_c{}^{-0.075}\left(\frac{\rho'_D}{\rho'_c}\right)^{0.5}$$

(25)

NOZZLE F : 97 - 0.076"

HOLD-UP AT REJECTION FROM ENTRY CONE

V.M.&P. SOLVENT INTO WATER

AMSCO "C" SOLVENT INTO WATER

Fig. 17.

DEVELOPMENT OF CORRELATION FOR LIMITING
FLOW IN 4" SPRAY TOWER

INTERCEPT TERM

NOZZLE A •
       D ▲
       F ✕
       W ✛

Fig. 18.

DEVELOPMENT OF CORRELATION FOR LIMITING
FLOW IN 4" SPRAY TOWER

SLOPE TERM

NOZZLE A •
       D ▲
       F ✕
       W ✛
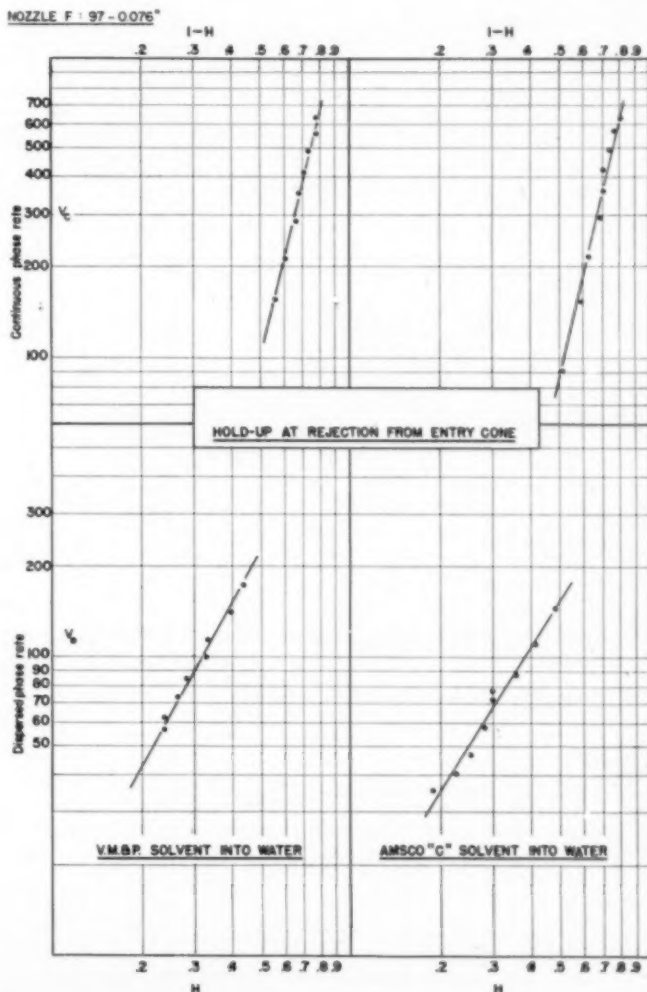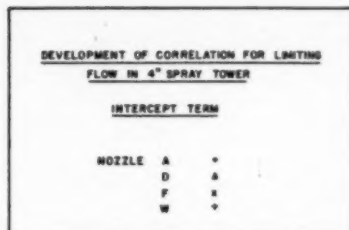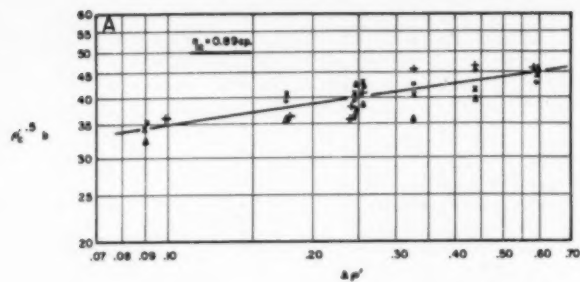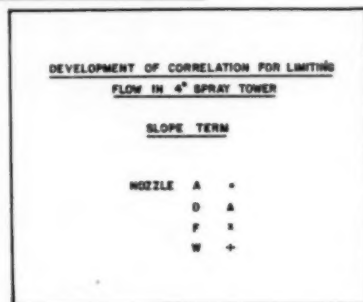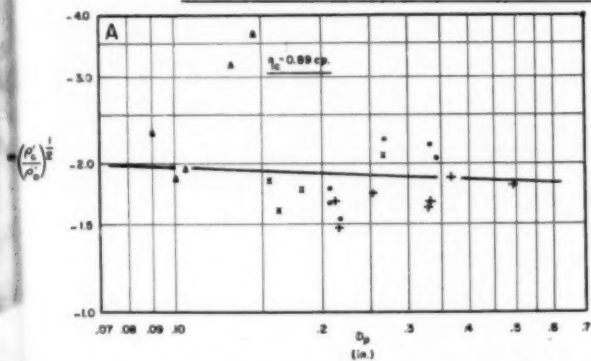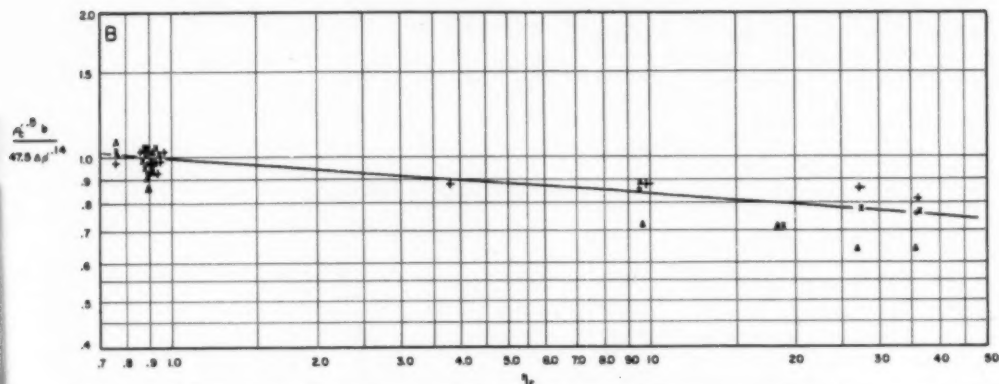
Fig. 19.
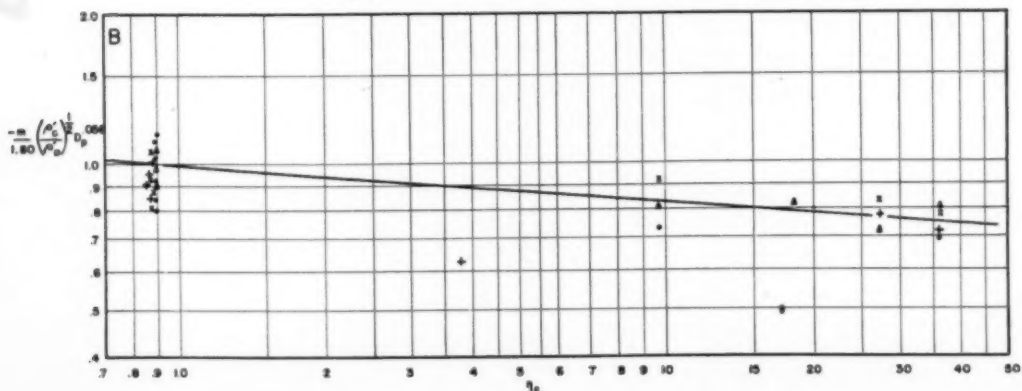
Therefore, the final form of the proposed correlation is

$$V_c{}^{1/2} = \left[-1.80 \, D_p{}^{0.688} \, \eta_c{}^{-0.087} \, \frac{\rho'_D}{\rho'_c}{}^{0.5} \right] V_D{}^{1/4}$$
$$+ \, [47 \eta_c{}^{-0.091} \, \Delta\rho{}^{0.14} \rho'_c{}^{-0.90}] \quad (26)$$

3. *Alternative Form.* Any correlation for spray towers would be of more value if drop size, the most difficult term to evaluate, were not involved. On plotting the observed slopes of the equations for the systems studied against spray area as in Figure 20 it appears that to a first approximation the slope is a function of the nozzle only (at constant continuous-phase viscosity). Introducing a nozzle constant *N*, the correlation becomes

$$V_c{}^{1/2} = -N \eta_c{}^{-0.087} \, V_D{}^{1/4} + 47 \eta_c{}^{-0.091} \, \Delta\rho{}^{0.14} \rho'_c{}^{-0.90}$$
$$(27)$$

Suggested values of *N* are:

Nozzle	N	Orifice Diam. in.	No. of Orifices/ sq.ft. of Tower Cross Section
A	1.9	.120	
F	2.1	.076	2620
D	2.8	.040	
W	1.7	.228	567

g. *Elgin and Foust Correlation.* Elgin and Foust (7) have proposed that the Wilhelm and Kwauk (12) correlation for fluidization is applicable to flooding in spray towers; this correlation consists of plotting the group $D^3 \rho c g \Delta\rho / \mu c^2$ against a modified Reynolds number $D \rho c U_s / \mu c$. Since this work is the first to cover a large range of physical properties and to measure the drop size of the dispersed liquid, the correlation should be fitted to the observed data. It has been found to plot best for rejection and for slip velocity defined as:

$$U_s = \frac{V_c}{(1 - H)} + \frac{V_D}{H} \quad (28)$$

The correlation is plotted on Figure 21.

h. *Comparison of Two Correlations.* Use of the proposed correlation with the nozzle constants is straightforward and easy and permits an estimation of maximum dispersed phase rate for any given continuous phase rate to less than 25%. For systems similar to those covered in this study and for the same nozzles, neither drop size nor holdup at flooding need be known.

Values of dispersed phase rate calculated at the same continuous phase rate using the Elgin-Foust correlation were found to deviate an average of 50% from the observed values; in general it has been found that the same curve served for both "flooding" and "rejection" and for several definitions of slip velocity.

Conclusions and Recommendations

In this work an attempt has been made to study holdup by settling and from pressure differential measurements; two different theoretical relationships between holdup and the phase rates at limiting flow have been proposed. These have indicated useful methods of representing data but require values of static velocity and more accurate measurements of holdup for further testing.

An empirical correlation for limiting flow, based on an extension of Bertetti's theory (2) is proposed. In the form suggested this may be used to estimate spray tower operation for a second system once the "nozzle constant" has been determined for one system, and eliminates the necessity for knowing drop size

SLOPES OF LIMITING FLOW EQUATIONS

REJECTION FROM ENTRY CONE
97 HOLED NOZZLES
WATER INTO ETHYLENE DICHLORIDE   ▲
ETHYLENE DICHLORIDE INTO WATER   □
V.M.&P. INTO WATER   ⊡
CARBON TETRACHLORIDE INTO WATER   +
AMSCO "C" INTO WATER   x
SOLVENT MIXTURE NO. I INTO WATER   x
     "   "   "   2   "   x
     "   "   "   3   "   x
CARBON TETRACHLORIDE INTO 36 cp
GLYCERINE SOLUTION

Fig. 20.

Fig. 21.

ELGIN-FOUST CORRELATION
LIMITING FLOW IN 4" SPRAY TOWER
REJECTION FROM ENTRY CONE
Slip velocity $u_s = \dfrac{V_o}{H} + \dfrac{V_c}{I-H}$

and holdup. Further testing and improvement of the correlation would be desirable.

The Elgin spray-tower design appears satisfactory but this work indicates that rejection rather than Elgin flooding is a more suitable limiting-flow condition. The Elgin correlation appears difficult to use especially since it depends on a knowledge of a significant drop diameter and on holdup. Although it has a better theoretical basis, as used here it appears to give less satisfactory results.

The large number of variables involved makes a theoretical approach difficult but emphasizes the need for further limiting flow studies on the spray tower and for further examination of the fundamentals of two liquid-phase flow.

Acknowledgment

Notation

b = intercept term of limiting flow equation

C = proportionality constant

Dp = drop size (feet for Elgin correlation; inches for proposed correlation)

g = acceleration due to gravity $(32.2 \times 3600 \text{ ft./hr.})/(\text{hr.})$

H = volume fraction holdup (cu.ft. dispersed phase/cu.ft. of tower volume)

η = phase viscosity (cps. 25° C.)

m = slope term of limiting-flow equation

μ = phase viscosity (lb.)/(ft.) (hr.)

n = a constant

p = pressure (lb./sq.ft.)

$\Delta p'$ = pressure differential (in.water)

ρ = phase density (lb./cu.ft.)

ρ' = specific gravity (25°/25°)

$\Delta \rho$ = density difference (lb./cu.ft.)

$\Delta \rho'$ = specific gravity difference

U_s = slip velocity (ft./hr.)

V = phase flow rate (cu.ft.)/(hr.) (sq.ft. of tower cross section)

V_o = static velocity (ft./hr.)

x = distance between drops (ft.)

z = effective height of tower (ft.)

Subscripts

C means continuous phase

D means dispersed phase

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FINE-SIZE, CLOSE-SPECIFIC-GRAVITY SOLID SEPARATION WITH THE LIQUID-SOLID CYCLONE[†]

J. J. MODER ‡ and D. A. DAHLSTROM

Northwestern Technological Institute, Evanston, Illinois

The rapid separation of close-specific-gravity, fine-size solid materials with liquids and the liquid-solid cyclone is demonstrated. This process utilizes a liquid which will float the less dense material and sink the more dense material without affecting the solids being separated during short contact periods. A slurry of the liquid and the solids to be separated is fed into one or more cyclones in series where the sink-and-float material is concentrated in the underflow and overflow streams respectively. The inherent advantages of this process, which requires only cyclones and conventional-type pumps, are low initial, repair, and operating costs, and extremely high capacity and separation efficiencies.

The design of liquid-solid cyclones for optimum solids separation is considered in the Cyclone Design section. The necessary recommendations and equations are presented to construct cyclones for any separation problem.

Operation of the liquid-solid cyclone is treated in the Cyclone Operation section, where it is demonstrated that an inlet pressure head of 40 ft. of fluid is optimum for cyclones of recommended design. Slurry solid concentrations should be less than 8% for best results. The operation of the cyclone with equal back pressures at the two outlet nozzles did not offset performance, permitting the operation of cyclones in series without intermediate pumps.

The effects of particle size, gravity difference between the solids and liquid, and distribution of the feed slurry to the overflow and underflow streams have been treated in the Solids Separation section. These results are presented in graphical form, from which calculations can be made as to the number of cyclones required to effect a specified separation. Predicted results based on the experimental conclusions are finally compared with actual cyclone achievements on an industrial material in the Sample Problem section and indicate good agreement.

THE separation of different solid materials is a common step in the preparation of a wide variety of products, and the means for achieving segregation are numerous. Some methods are of a general nature, while others are highly specific, capitalizing on some unique chemical or physical property of the materials. Sink-float methods for solids of different specific gravity are a common example of the latter type.

This process separates materials of different specific gravities by using liquids or heavy media slurries which float the lower specific gravity solids and sink the higher specific gravity solids. A high degree of separation is possible when sufficiently large gravity differences between solids are present or when the solids are coarser than ¼ in. Similar efficiencies are generally either unobtainable or uneconomical outside the above ranges if only the force of gravity is employed in the separation process. Use of centrifugal force to improve efficiency and capacity by increasing the settling velocities of fine particles is possible but in many cases is too costly with mechanical centrifuges. To this end it was proposed to utilize the high centrifugal force of the liquid-solid cyclone to effect a high quality and capacity separation at a low cost. By this method, the sink material is collected in the underflow stream drawn from the apex of the cyclone cone, and the float material is collected in the overflow stream drawn from the center of the cyclone vortex. Due to the simple design of the liquid-solid cyclone, the initial equipment costs are low. Since there are no moving parts in the system, other than the feed pumps, operation and maintenance costs are also low. The capacity per square foot of floor space is extremely high, as the cyclone is capable of handling up to 400 gal./(min.)(sq.ft. of cross-sectional area). The separation efficiency per cyclone compares favorably with other methods. Furthermore, as determined herein, the cyclones can be economically operated in series arrangements, making possible any degree of separation.

Recently, considerable acceleration in the beneficiation of minus ¼-in. solids has occurred, due primarily to economic and sales necessity. Admirable progress has been made in the mineral and coal industries in lowering production costs on these difficult sizes. However, all such low-cost methods are generally restricted to materials, ores, and coals differing by at least 0.1 or more in specific gravity between solids if high separation efficiency is to be maintained. Several food, agricultural, pharmaceutical, and chemical products approach closely (up to 0.01 or less) the specific gravity of the undesirable material accompanying their native or synthetic state, resulting in a presently difficult and costly separation. Accordingly, this investigation was made to ascertain

Fig. 1. A three-in. experimental cyclone.

Labels on figure:
ADJUSTABLE LENGTH OVERFLOW NIPPLE

STANDARD PIPE COUPLING, PLATES WITH DIFFERENT SIZE COUPLINGS USED TO VARY THE OVERFLOW NOZZLE DIAMETER.

STANDARD PIPE SIZES OF $\frac{1}{8}$, $\frac{1}{4}$, $\frac{3}{8}$. AND $\frac{1}{2}$ ARE WELDED INTO THE CYCLONE AT 90° INTERVALS ABOUT THE CIRCUMFERENCE. ONLY ONE SUCH PIPE IS SHOWN IN THIS DRAWING. BRASS PLUGS ARE PLACED IN THE NOZZLES NOT IN USE.

STANDARD 3" PIPE

STANDARD 3" PIPE FLANGE

MILD STEEL

ADJUSTABLE UNDERFLOW DIAMETER

Test No.	% Slurry To OF	% Float To UF	% Sink To UF	Slurry Conc. in % Solids Feed	Over- flow	Under- flow
IX-1	48.0	None Present	93.9	0.33	0.04	0.62
IX-2	48.0	80.3	None Present	0.30	0.47	0.12
IX-3	48.0	80.2	93.2	0.40	0.33	0.40
IX-4	48.0	80.5	95.2	1.05	0.85	1.27
IX-5	48.0	79.9	94.6	2.95	2.41	3.55
IX-6	48.0	79.4	95.4	4.58	4.05	5.17
IX-7	49.7	77.0	95.7	7.88	6.95	8.83

6. Height of cylindrical section
7. Inlet nozzle angle
8. Distance between inlet nozzle and top of cyclone
9. Cyclone diameter

To facilitate the investigation, the 3-in. cyclone pictured in Figure 1 was constructed, which permitted alteration of the most important factors 1 to 4 listed here. The remaining variables of lesser importance were either sufficiently treated in the literature or examined as follows to arrive at the final design of Figure 1.

Cyclone Included Angle. Tests reported by Yancey (12) and Dahlstrom (4) indicate that decreasing cyclone included angle increases cyclone capacity and improves solids separation. This result is probably caused by a smoother transition from the cylindrical to the conical section. Literature indicates that angles smaller than 15° negligibly enhance separation efficiency. This was, accordingly, considered optimum for this work.

Height of Cylindrical Section. Test results of Dahlstrom (4) revealed that increasing the height of the cylindrical section from that required for the inlet nozzle entry by 6 to 10 in. had the same effect on cyclone capacity as decreasing the cyclone included angle. The same explanation as just given applies, and a cylindrical section of approximately 7 in. was employed.

Inlet Nozzle Angle. Preliminary observations on a 2-in. diam. glass cyclone with inlet angles from 0° to 10° exhibited no effect on the solids separation or pressure drop. Since this variable is relatively unimportant, the criterion of descending one inlet nozzle diameter per revolution was used for design purposes.

Distance Between Inlet Nozzle and Cyclone Top. No literature recommendations were found on this subject. Visual observations made on a 2-in. diam. glass cyclone indicated a fluid rotation in this region which seemed to have a zero vertical velocity component. A small amount of fluid must, however, be continually transferred to this region to supply energy to overcome frictional losses. This could result in a build-up of solids in this region, which increases the sink losses in the overflow stream if the overflow nozzle is incorrectly

feasibility, predict performance and determine means of calculating optimum design and energy requirements for the application of sink-float cyclone methods to low-cost, high-quality treatment of close-specific-gravity, fine-size solids.

With this objective in mind, the investigation was broken down into four sections: Cyclone design, cyclone operation, solids separation, and industrial application. In the Cyclone Design section, certain dimensions were investigated to determine the optimum design and necessary design equations. Under Cyclone Operation other dimensions, which were better considered as operating factors, were investigated along with the variables of inlet feed pressure and the effects of possible cyclone series arrangements. In the Solids Separation section, the particle size and particle gravity difference were considered, based upon the previously found optimum cyclone design and operating conditions. Finally a two-stage cyclone process for an industrial material was designed to effect a product meeting high purity specifications. Actual results were then compared with predicted values in the Industrial Application section.

Liquid-Solid Cyclone

The liquid-solid cyclone is similar in construction and operation to the older and more familiar gas cyclone dust collector. It consists of a cylindrical section in which a tangential inlet nozzle is located. One end of this section is covered with a flat plate fitted with a centrally located nozzle termed the overflow nozzle. The other end is fitted with a truncated cone, the apex of which forms an outlet termed the underflow nozzle. When a fluid is fed through the inlet nozzle, a rotating flow pattern is set up inside the cyclone and the flow distributes itself to take the path of least resistance. This path is a double vortex. One vortex moves downward along the cyclone wall and leaves through the underflow nozzle, while the other moves upward in the center of the cyclone and exits via the overflow nozzle. Cyclone construction, particularly the dimensions of the just-mentioned nozzles, as well as the inlet pressure head, are thus the important factors in controlling the internal flow pattern.

The high centrifugal forces generated by the flow pattern tend to concentrate the sink material at the cyclone wall, and thus to the underflow while the float solids are forced to the core and then migrate to the overflow.

Cyclone Design

Equipment. Literature and preliminary studies indicated the following design variables as important in determining optimum cyclone construction and operation.

1. Inlet nozzle diameter
2. Overflow nozzle diameter
3. Underflow nozzle diameter
4. Vertical position of overflow nozzle
5. Cyclone included angle

located. Accordingly, this dimension was kept to a minimum on all cyclone designs.

Cyclone Diameter. The subject of cyclone diameter is one of considerable controversy in the literature. Conclusions of Shepherd and Lapple (10) and Dahlstrom (4) have both experimental and theoretical basis. They have found cyclone pressure drop and solids elimination to be entirely independent of cyclone diameter within reasonable cyclone design. Equations were developed and proved in both cases, wherein separation efficiency and energy loss depended entirely on inlet and overflow diameter and capacity.

Some authors have reasoned that smaller diameter cyclones with corresponding small nozzles, result in a higher centrifugal field and thus better solids elimination, than cyclones of larger size. At the same time, all literature appears to be in agreement that the critical separation radius occurs at approximately the overflow radius, which is well removed from the cyclone wall, thus minimizing the importance of cyclone diameter. Furthermore, experimenters concluding that cyclone diameter is a significant variable, have not investigated different inlet and overflow nozzle diameters at constant cyclone diameter, but have utilized geometrically similar cyclones. This approach is limited in any process design and lends no rigorous basis for correlation. A cyclone diameter of 3 in. was chosen for experimental purposes, as it was a convenient size for laboratory studies and yet large enough to give data representative of large-scale cyclones.

Methods and Procedure

Consideration of cyclone capabilities dictated that the solid materials used in the theoretical study should have the following properties.

1. Particle size range from 20 to 100 mesh
2. Particle shape, spherical
3. Variation in specific gravity from particle to particle less than 0.0005
4. Particle specific gravity in the range 1.00 to 1.20 to permit use of water or aqueous, inorganic salt solutions as the liquid medium

Plastic beads composed of a copolymer of polystyrene and divinyl benzene answered all the requirements just mentioned. The specific gravity of the beads was found to be 1.046, permitting a water solution of magnesium sulfate as the liquid. Complete
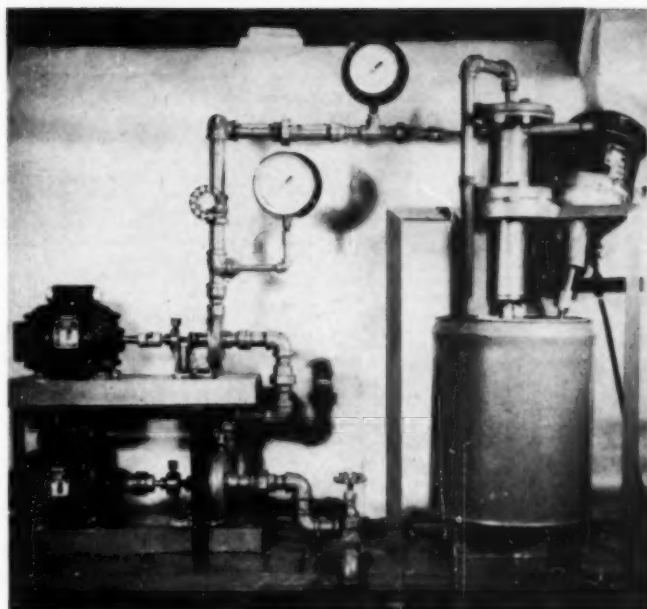

Fig. 2.

wetting of the solid was insured in all tests by use of Aerosol OT to make a 0.005% strength solution.

To facilitate analytical work, only one solid, either sink or float, was tested at one time. The validity of this technique was first verified as will be seen. This technique makes it possible to obtain both sink-and-float data with only one gravity material merely by varying the specific gravity of the liquid above and below that of the solids.

The equipment setup is shown in Figure 2, wherein the cyclone is operated in a closed system. The overflow and underflow streams are collected and mixed in the same tank and continuously recirculated as feed. The procedure consisted of obtaining rate

measurements of the overflow and underflow streams, from which the volume split and the cyclone capacity could be calculated, and overflow and underflow samples for solids separation evaluation. After analyzing for solids concentration, the data were then combined with the rate data to determine solid distribution or recovery in the overflow and underflow streams.

Having developed a reliable test procedure, the validity of the assumption that solids separation is independent of the feed composition (the per cent sink and per cent float solids making up the feed solids) was tested. The specific gravity of the plastic beads increases upon standing in solvents such as carbon tetrachloride. This fact was used to make a portion of the beads higher

Chemical Engineering Progress

TABLE 2

EFFECT OF OVERFLOW NOZZLE LOCATION

Cyclone Diameter 3"

Inlet Nozzle Diameter 0.378"

Overflow Nozzle Diameter 0.503"

Particle Size Diameter -35 -40 Mesh

$(\rho_s - \rho) = 0.0100$

$\rho_s = 1.046$

Test No.	Material	Length of Overflow Nozzle Inches	% Slurry To UF	% Solids To UF	UF Nozzle Diameter Inches	(GPM)	Inlet Pressure P.S.I.
VI-1	Sink	0.5	25.1	85.4	0.323	8.40	18.0
VI-4	"	1.0	25.0	86.3	"	8.51	"
VI-5	"	2.5	25.8	87.3	"	8.59	"
VI-8	"	5.0	26.1	86.8	"	8.56	"
VI-2	"	0.5	47.2	92.9	0.421	9.07	"
VI-3	"	1.0	47.7	93.4	"	9.03	"
VI-6	"	2.5	47.3	64.6	"	8.07	"
VI-7	"	5.0	46.7	95.4	"	9.08	"
VI-9	Float	0.5	47.2	19.9	"	9.07	18.4
VI-11	"	1.0	47.7	19.9	"	9.03	"
VI-15	"	2.5	47.3	19.7	"	8.07	"
VI-16	"	5.0	46.7	18.1	"	8.08	"
VI-10	"	0.5	70.3	58.1	0.267	9.76	"
VI-12	"	1.0	70.3	58.5	"	9.79	"
VI-14	"	2.5	70.0	61.4	"	9.96	"
VI-13	"	5.0	70.5	75.8	"	10.10	"

TABLE 3

EFFECT OF VOLUME SPLIT AND o/b RATIO

ON THE PRESSURE DROP CONSTANT K

Run No.	Cyclone Diameter Inches	o	b	o/b	GPM
I-1a	3"	0.378	0.503	0.75	8.95
62A	5"	0.636	0.636	1.00	24.2
62B	8"	1.240	1.240	1.00	66.0
A	2"	0.406	0.219	1.86	2.99
52	7"	1.610	0.824	1.96	38.2

Run No.	Liquid Specific Gravity	Inlet Pressure p.s.i.	% Vol. to UF	K	K Graph	% Dev.
I-1a	1.0390	26.0	11.5	5.23	5.24	+0.2
62A	1.460	30.0	70.2	7.90	7.00	-12.9
62B	1.460	23.3	63.3	7.45	6.74	-9.5
A	1.409	14.0	21.2	5.53	5.44	-1.6
52	1.460	24.0	11.7	4.82	5.33	+10.6

in specific gravity than the untreated beads, thus supplying two materials of different specific gravities. Results of these tests are presented in Table 1 and point out that solids separation for both sink-and-float material is the same whether the solids are tested alone or in mixtures. The tests also indicate that particle separation is relatively independent of feed slurry solids concentration up to at least 4% solids. No effort was made, therefore, to hold the feed solids concentration to a precise level, but allowed to vary between $0.6 \pm 0.15\%$.

Overflow Nozzle Location. This factor was analyzed by inserting different nipple lengths in the overflow bushing of Figure 1. Results of these tests are given in Table 2 and Figure 3. Data indicate that positioning the overflow even with the inlet nozzle will yield almost maximum separation regardless of volume split to the underflow. Slight improvement can be experienced by lowering the overflow still further with volume splits to the underflow of less than 50%, but severe injury of float recovery occurs at high volume splits. Accordingly, all other tests were performed with the overflow located level with the inlet axis to expedite the work. In actual practice the overflow should extend about ½ cyclone diam. below the inlet at 50% or less volume split to the underflow for maximum recovery.

Inlet and Overflow Nozzle Diameter. In the application of this method of solids separation it will be necessary to design cyclones having a specified capacity for a given inlet pressure head. A quantitative evaluation of the significant cyclone dimensions is, therefore, necessary. A starting point for the development of this correlation is the equation presented by Dahlstrom (3) indicating inlet and overflow nozzle diameters to be the design factors of major importance.

$$\frac{gal./min.}{\sqrt{F}} = K(eb)^{0.9} \qquad (1)$$

The proportionality constant K was shown to be a function of minor design variables.

To test the validity of the expression for this application where much larger volume splits to the underflow are utilized, rate measurements of this entire investigation have been tabulated in Table 3. A semilog plot of these data, given in Figure 4, shows that K values are relatively constant for volume splits below 30% and check reasonably well the values reported in the literature. The plot also illustrates the significant trends of the K values with volume split and e/b ratio. The increase in K values with increasing volume splits is in accord with theory, as the underflow stream does not have as high a kinetic energy level as the overflow stream.

Least squares regression equations have been fitted to these data yielding the following equations.

$$K = 4.85E^{0.0001(Y.S)}; \quad e/b = 0.75 \text{ to } 1.00 \qquad (2)$$

$$K = 5.60E^{0.0004(Y.S)}; \quad e/b = 1.25 \text{ to } 1.35 \qquad (3)$$

$$K = 5.35E^{0.0005(Y.S)}; \quad e/b = 1.68 \text{ to } 2.11 \qquad (4)$$

The correlation coefficients for these expressions are 0.91, 0.87, and 0.67, respectively, which are highly significant in the statistical sense. The "standard error of estimate" leads to a 95% confidence interval for predicted K values of $K \pm 0.10\ K$. Thus a design safety factor of $\pm 10\%$ is adequate for the above-listed equations. Important restrictions are a 15°-cone angle and a cylindrical section of approximately two cyclone diameters.

Underflow Nozzle Diameter. It was found that close-gravity solids separation is greatly influenced by volume split between the two product streams which is primarily controlled by the overflow and underflow nozzle diameters. Since the former also affects cyclone pressure drop, it is more convenient to control the volume split by varying the underflow nozzle diameter which has relatively little effect upon cyclone energy loss.

The overflow nozzle diameter and volume split are obviously significant variables in any correlation to predict underflow diameter. It is also known that increasing the vortex strength by increasing the cyclone pressure drop, decreases the volume split, although cyclone feed rate (gal./min.) proved to be a better variable for correlation purposes. The proposed equation is then

$$\frac{(\%UF)}{(\%OF)} = C' \frac{(u)}{(e)}^{\alpha} (gal./min.)^{\beta} \qquad (5)$$

To verify this expression, values of $(\%UF)/(\%OF)$ were plotted on log-log paper as a function of $(u)/(e)$ for tests having a constant (gal./min.). Results exhibited a straight-line correlation with a slope of 4.4 equal to α above.

Similarly, $(\%UF)/(\%OF)$ was plotted as a function of (gal./min.) with constant parameters of $(u)/(e)$ obtained from
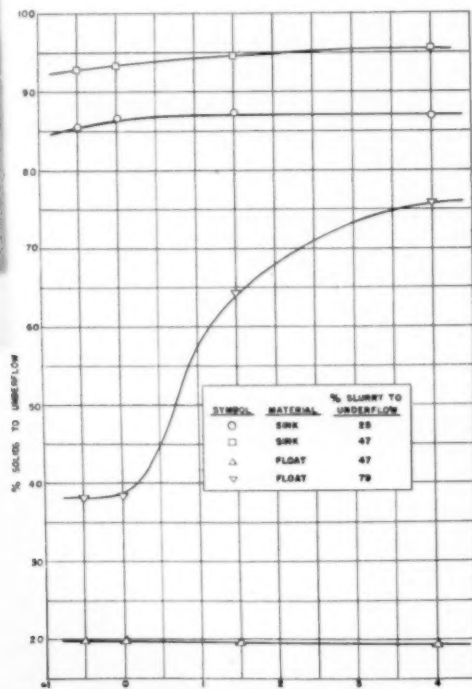
Fig. 3. Effect of overflow nozzle on the solids separation.
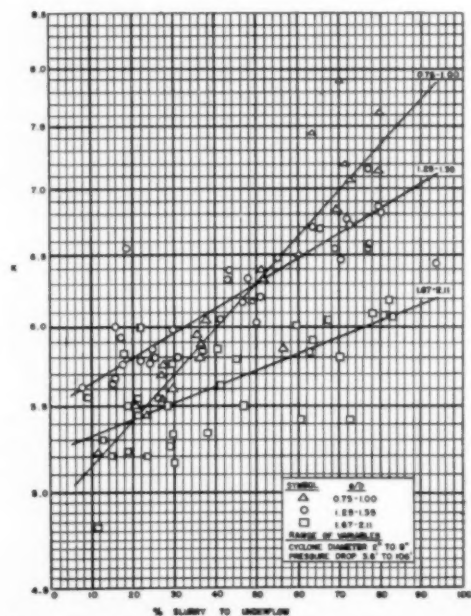
Fig. 4. K as a function of % slurry to underflow with parameters of e/b.

further runs. Again a straight-line correlation was obtained, the slope of 0.44 being equal to β. Equation (5) then can be written with the exponents shown above as follows:

$$\frac{(\%UF)}{(\%OF)} = C' \frac{(u)^{4.4}}{(e)} \, (\text{gal./min.})^{0.44}$$

(6)

Solving for underflow diameter u:

$$u = C \frac{(\%UF)^{0.30}}{(\%OF)} \, (\text{gal./min.})^{0.10} (e)^{1.00}$$

(7)

Data of Table 4 were then plotted according to Equation (7) on log-log paper in Figure 5. A straight-line correlation was obtained with the expected slope of 1.00 and an intercept value for C of 0.662.

The mean deviation of calculated u values was ±3.6% with maximum deviations of +15% and −12%. This correlation covered a range of cyclone diameters from 2 to 8 in., u values from 12 to 120 ft. of fluid.

Cyclone Operation

Table 1 indicates that sink recovery is not impaired by increasing solids concentration in the range covered. The float recovery, however, begins to decrease slightly for inlet and overflow slurry concentrations above 3% solids. Undoubtedly, this is due largely to the entrapment of significant amounts of float solids by sink solids when the latter are present in large concentrations.

The above data, of course, apply to spherical particles. Later reported tests on industrial material composed of con-

cave plates and fibrous needle-shaped material, both of which had an extremely low sphericity, indicated that solids separation was appreciably affected by concentrations in excess of 3%. The phenomenon was small for sink material, but more prominent with float solids. The qualitative recommendation then follows. For solids (especially float material) of extremely low sphericity, the solids concentration in any stream should be kept at 3% or below to maximize separation efficiency. As the sphericity and coarseness of the particles increase, concentration may be increased to at least 8% while still maintaining maximum recovery.

It should be emphasized at this point that considerably higher concentrations can be employed with only small injury to separation efficiency. Economics and product purity should be the final judge after pilot tests have been performed on the material in question.

Effect of Nozzle Dimensions and Cyclone Feed Rate on Solids Separation. It was originally hypothesized that solids separation would be a function of the inlet and overflow nozzle diameters, the volume split, and the cyclone feed rate as in other cyclone applications. Many tests were made in which one of the above variables was changed at constant levels of the other factors as given in Table 5. No consistent trends could be noted in these data necessitating a different approach. By graphical interpolation of the data in Table 5, values of the per cent solids reporting to the underflow stream were obtained as a function of cyclone inlet pressure at volume splits of 20%, 50%, and 80%. These values are presented in Table 6 and Figure 6. Examination of the latter figure leads to the striking conclusion that solids separation, in the ranges of operation considered, is a function of the cyclone inlet pressure head and volume split, and
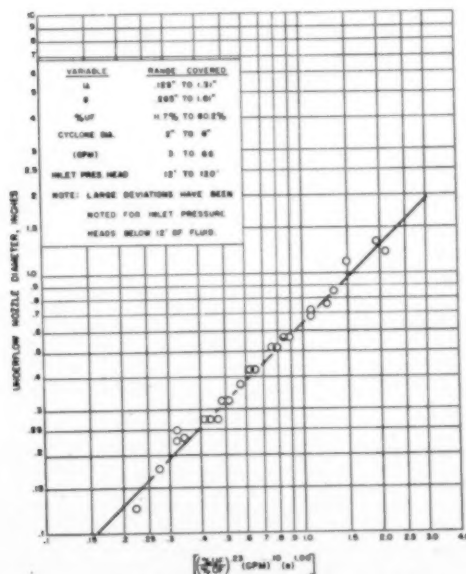
Fig. 5. Correlation for the calculation of cyclone underflow nozzle diameter.
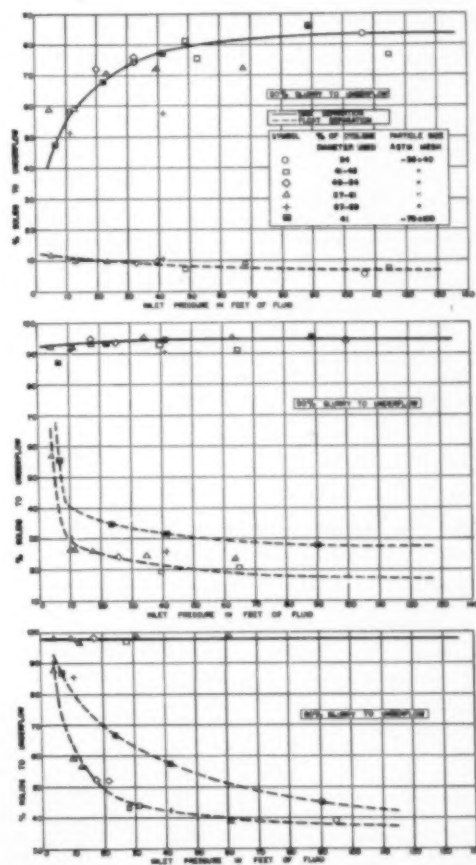
Fig. 6. Effect of inlet pressure and % cyclone diameter used on solids separation.

Fig. 7. Multiple cyclone arrangement, *k* stages, for solids separation.
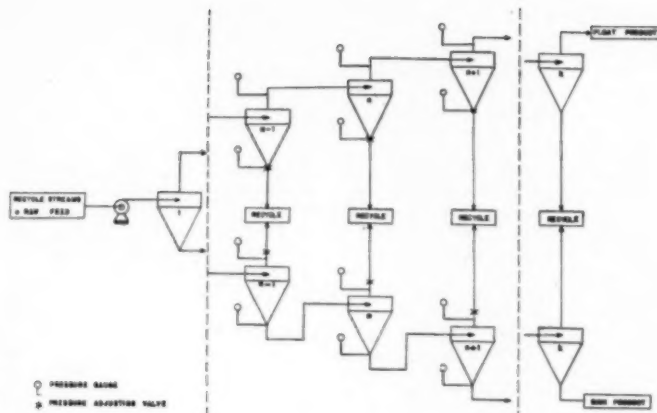
independent of cyclone inlet and over-flow nozzle diameters. This differs from results obtained with the liquid-solid cyclone in the mineral and coal industry, but can probably be best explained by the greater retention time of the large cyclone offsetting the lower centrifugal forces with solids near the classification point.

The points plotted in Figure 6 have been grouped according to the per cent of the cyclone diameter used which is defined by Equation (8).

% of Cyclone Diam. Used

$$= 100 \left[\frac{2b + e}{D_e} \right]$$

(8)

Examination of Figure 6 shows generally better separation for tests when the % of Cyclone Diameter Used was small and marked impairment for the highest range (67% to 69%) investigated.

The authors feel that for each cyclone diameter, an optimum combination of inlet and overflow nozzle diameters exists although quantitative data are not available to establish this point. Figure 6 does show that for tests where less than 50% of the cyclone diameter was used, different nozzle combinations had only a slight effect on solids separation. In general then, the % of the cyclone diameter used, should be kept below 50% and *e* and *b* should be chosen to

give e/b ratios between 1 and 2. It will be noted by referring to Equation (8) that larger total nozzle areas can be obtained and still satisfy the criterion of using less than 50% of the cyclone diameter by using high values of the e/b ratio. Thus, solving the two criteria below in terms of cyclone diameter

$$2b + e = \frac{D_e}{2} \quad e/b = 2$$

one can say that $e = D_e/4$ and $b = D_e/8$ will yield a cyclone design for maximum capacity and solids separation.

Optimum Inlet Pressure Head. Another point of importance which is clearly brought out by Figure 6 is the effect of inlet pressure on solids separation. In general, for all volume splits inlet pressures greater than 40 ft. of fluid have little effect on increasing solids separation and for volume splits around 50%, the optimum inlet pressure is much lower. As indicated later, cyclones in series are considerably more effective in improving solids separation than using higher inlet pressures. Accordingly, an inlet pressure of 40 ft. was considered as optimum for any volume split and was used exclusively in the remainder of the investigation. Naturally, if excess pressure is available, it can be utilized in increasing cyclone capacity.

Effect of Particle Size on Optimum Inlet Pressure. To establish the fact that the conclusions mentioned on optimum

TABLE 4

UNDERFLOW NOZZLE DIAMETER CORRELATION

Test No.	Cyclone Diameter Inches	b	e	u
II-1	3"	0.265"	0.503"	0.274"
A	2"	0.219	0.406	0.214
62A	5"	0.636	0.636	0.680
53	7"	0.824	1.610	1.31
62A	8"	1.24	1.24	1.20

Test No.	Inlet Pressure p.s.i.	GPM	% Slurry to UF	Calcu-lated u	% Error
II-1	55.6	8.93	12.7	0.266	-2.9
A	14.0	2.99	21.2	0.222	-5.1
62A	30.0	24.2	70.2	0.704	+3.5
53	24.0	41.7	29.0	1.260	-3.8
62A	23.3	66.0	63.3	1.370	+14.2

TABLE 5

EFFECT OF INLET PRESSURE AND % OF CYCLONE DIAMETER USED ON SOLIDS SEPARATION

Cyclone Diameter 3"
(ρs - ρ) = 0.0100 ρs = 1.046
Overflow Nozzles Even with Inlet Nozzle

Test No.	GPM	Inlet Pressure p.s.i.	% Slurry to UF	% Solids to UF
V-17	21.2	18.0	16.9	51.6
V-18	21.4	"	29.8	73.5
V-19	22.6	"	43.0	86.6
V-20	23.9	"	63.5	97.0
V-21	21.2	"	22.6	10.1

Test No.	Particle Size ASTM Mesh	Inlet Nozzle Diameter Inches
V-17	-35 + 40	0.628
V-18	"	"
V-19	"	"
V-20	"	"
V-21	"	"

Test No.	OF Nozzle Diameter Inches	UF Nozzle Diameter Inches	Material
V-17	0.544	0.518	Sink
V-18	"	0.616	"
V-19	"	0.713	"
V-20	"	0.850	"
V-21	"	0.567	Float

TABLE 6

EFFECT OF INLET PRESSURE AND % OF CYCLONE DIAMETER
USED ON SOLIDS SEPARATION - INTERPOLATED VALUES

Cyclone Diameter 3"
(ρs - ρ) = 0.010   ρs = 1.046

SINK DATA

Particle Size ASTM Mesh	%Slurry to UF	% Solids to UF	Inlet Pressure Head Feet of Fluid	% of Cyclone Diameter Used
-35-40	20	83.8	106.3	33.7
"	50	94.3	100.3	33.7
"	80	96.9	94.5	33.7
-70-100	20	47.7	6.7	41.1
"	50	87.0	6.7	41.1

TABLE 7

EFFECT OF BACK PRESSURE ON CYCLONE OPERATION

3" Diameter Cyclone

Test No.	Particle Size ASTM Mesh	Liquid Sp.Gr.	Solid Sp.Gr.	Inlet Pressure p.s.i.	OF Pressure p.s.i.	UF Pressure p.s.i.	GPM	2	2	3	% Slurry to UF	% Solids to UF
VIII-1a	-50-70	1.0510	1.0463	36.0	18.0	18.0	9.19	0.503	0.378	0.460	46.8	84.5
VIII-1b	"	"	"	"	"	"	"	"	"	"	"	36.8
VIII-3a	"	"	"	"	"	"	"	"	"	"	"	32.9
VIII-3b	"	"	"	"	"	"	"	"	"	"	"	37.1
VIII-2a	"	"	"	"	"	0.0	"	"	"	0.274	68.2	86.1
VIII-2b	"	"	"	"	"	"	9.12	"	"	"	"	83.7
VIII-4	-40-50	1.0750	1.2480	34.0	0.0	"	14.88	0.628	0.503	0.460	37.9	96.9
VIII-5	"	"	"	44.0	20.0	20.0	14.56	"	"	"	33.2	96.0
VIII-6	"	1.0590	"	34.5	0.0	0.0	14.58	"	"	"	35.5	8.9
VIII-8	"	"	"	35.0	20.0	20.0	14.25	"	"	"	35.1	9.7

inlet pressure are independent of particle size in the range considered in this investigation, tests were made upon −70 +100 mesh material with results as indicated in Table 5 and Figure 6. Two significant points are apparent. First, the optimum inlet pressure head was at the same level as the tests based upon −35 +40 mesh material. Second, the float separation curves, although of the same general shape as before, were shifted upward as expected for smaller diameter particles. The sink points, on the other hand, showed no appreciable deviations from the previous curve. Because this appears at first glance to be contrary to theory, the phenomenon will be explained in detail in a later section.

Effect of Back Pressure on Cyclone Operation. To obtain solids separations greater than possible by a single pass through the cyclone, additional cyclones in series are required. This can be accomplished by feeding the underflow and overflow streams of the primary cyclone into two secondary cyclones. Advantages of accomplishing this without intermediate pumps are many. Fewer slurry tanks, piping, automatic controls, floor space and pumps are required, and most important is the resulting greater ease of operation. Elimination of the intermediate pumps can be accomplished by feeding the exit streams of the primary cyclone directly into the secondary

cyclones. This type of operation necessitates operating the first cyclone with back pressure at both outlets sufficient to operate the secondary cyclones. Tests were made with gate valves and pressure gauges in the exit lines of the 3-in. diam. experimental cyclone enabling adjustment of the back pressures on the cyclone overflow and underflow streams. Results presented in Table 7 showed those obtained with back pressure at only one exit nozzle gave unsatisfactory results. However, those experienced when back pressures were approximately equal did not differ significantly from results obtained when the nozzles discharged at atmospheric pressure. Accordingly, if the cyclones in a series arrangement are correctly designed with respect to pressure drop, so that any one cyclone possesses equal pressures at overflow and underflow nozzles, such a flow system is not only feasible, but also recommended for maximum economy and simplicity.

Further analyses of the data show that the pressure-drop Equations (1) to (4) and the underflow nozzle diameter Equation (7) apply with the same accuracy to equal back pressure cyclone operation permitting use of these equations in the design of such cyclones. A general cyclone arrangement for *k* stages of separation is shown in Figure 7. Consider the case when *k* = 2. The

design goal is to have the secondary cyclones constructed to give equal pressure drops with feed rates as specified by the primary cyclone feed rate and volume split. It is obvious that the capacities of the secondary cyclones will have a marked influence on the volume split of the primary cyclone, more so than the underflow nozzle diameter, necessitating accurate pressure-drop design. From the equation developed, it will be entirely possible to construct cyclones possessing equal inlet and outlet pressures for each stage, making pressure-adjusting valves unnecessary.

Solids Separation

Results of this section will make it possible to estimate solids separation per cyclone obtainable for any particle size or specific gravity difference in the range investigated. This, in turn, will fix the number of stages required for a particular problem as indicated in Figure 7.

Effect of Particle Size, Gravity Difference, and Volume Split on Solids Separation. To obtain an estimate of the significance of the above factors and their possible interactions, a preliminary factorially designed experiment was performed. This design included all possible combinations of the variables at two levels of particle size, three levels

TABLE 8

ANALYSIS OF VARIANCE FLOAT DATA

Dependent variable is, "% Float Solids to UF"

The following nomenclature is used in this 3-factor experiment.

D_1 = -25 +30 mesh particle size

D_2 = -50 +70 " " "

G_1 = specific gravity difference of .0040 to .0046

G_2 = " " " " " .0070

G_3 = " " " " " .0660 to .0698

S_1 = 25.5% slurry to UF

S_2 = 48.0% " " "

S_3 = 70.4% " " "

S_4 = 80.1% " " "

	D_1			D_2		
	G_1	G_2	G_3	G_1	G_2	G_3
S_1	14.0	8.4	0.1	18.5	11.4	0.8
S_2	30.3	22.4	0.3	34.8	22.8	3.1
S_3	42.6	34.9	0.9	54.0	44.0	9.7
S_4	52.4	48.4	7.6	82.7	80.2	60.4

TABLE 9

ANALYSIS OF VARIANCE FLOAT TABLE

Source of Variance	Degrees of Freedom	Sums of Squares	Mean Squares	Components of Variance
S□	3	7,202.09	2,400.67	$\sigma_b^2 + g\sigma_{sd}^2 + d\sigma_{sg}^2 + dg\sigma_s^2$
D*	1	1,068.00	1,068.00	$\sigma_b^2 + g\sigma_{sd}^2 + s\sigma_{dg}^2 + sg\sigma_d^2$
G*	2	4,161.97	2,080.99	$\sigma_b^2 + d\sigma_{sg}^2 + s\sigma_{dg}^2 + sd\sigma_g^2$
S x D*	3	1,296.51	432.17	$\sigma_b^2 + g\sigma_{sd}^2$
S x G*	6	524.43	87.40	$\sigma_b^2 + d\sigma_{sg}^2$
D x G	2	28.37	14.19	$\sigma_b^2 + s\sigma_{dg}^2$
Residual	6	129.81	21.64	σ_b^2
Total	23	14,411.18		

* Significant at 5% level
** Significant at 1% level

□ Due to the significance of the S x D and S x G interactions, there is no straightforward method of testing the significance of this variable; however, its significance has been established by other data and will be considered so here.

* Significance test is very insensitive here, due to the large mean square for the S x D interaction and also due to the fact that the D variable has only one degree of freedom. Significance of this variable has been established by other tests and will be considered so here.

---

of specific-gravity difference, and four levels of volume split for both sink and float material. The original float data are given in Table 8 and the results of the "Analysis of Variance" in Table 9. The latter indicated that all main variables plus the volume split X particle size and volume split X gravity difference interactions are significant. The two significant interactions emphasize that effects of particle size and gravity difference on float solids separation are dependent upon the level of the volume split. Accordingly, for design and estimation purposes, results are presented in graphical form by plotting % float solids reporting to the overflow as a function of gravity difference with parameters of particle size and volume split.

Additional data taken to establish firmly the curves described are presented in Table 10 and in Figure 8 as % solids reporting to the underflow as a function

of volume split with parameters of particle size and gravity difference. Significance of particle size and gravity difference is clearly brought out by the displacements of these curves and the importance of volume split is shown by their positive slopes. The volume split X gravity difference and volume split X particle size interactions are also emphasized by the differences in shapes of these curves. By cross-plotting, Figures 9a, 9b, and 9c were prepared in which % float solids reporting to the overflow has been plotted as a function of gravity difference with parameters of particle size and volume split. From these graphs, % float solids reporting to the overflow can be predicted for particle sizes in the range −25 +100 ASTM mesh, volume splits between 15% and 75%, and gravity differences from 0.000 to 0.075 for float material and 0.000 to 0.045 for sink material.

The sink data were analyzed in the

same manner as the float data shown here. Results presented in Table 11 and 12 indicate that particle size and its two interactions, particle size X volume split and particle size X gravity difference are not significant. Although contradictory to theory, this phenomenon agrees with the results previously indicated in Figure 8, where −70 +100 mesh material gave separations approximately equal to those obtained with −35 +40 mesh material.† Additional data were taken to verify further this conclusion and are presented in Table 10. No consistent trends with respect to particle size could be noted, and so an average of the data obtained was used for correlation purposes.

The above analysis also showed the volume split X gravity difference interaction to be highly significant. Thus, it was decided to present the sink separation data in graphical form by plotting % sink solids reporting to the underflow as a function of gravity difference with parameters of volume split. This correlation is shown in Figure 10 from which % sink solids reporting to the underflow can be predicted for particle

TABLE 10

EFFECT OF PARTICLE DIAMETER AND $(\rho_s - \rho)$ ON SEPARATION

Cyclone Diameter 3"
Overflow Nozzle 0.503"
Inlet Nozzle 0.378"
Inlet Pressure 40' Fluid

SINK TESTS

Test No.	% Slurry to UF	% Solids to UF	$(\rho_s - \rho)$	Particle Size ASTM Mesh
VII-53b	15.6	71.2	.0115	-25+30
II-5	"	74.7	.0100	-35+40
VII-1	"	77.7	.0100	-40+50
VII-96	"	77.8	.0114	-50+70
IV-21	"	71.0	.0100	-70+100

† Recent work has yielded a logical explanation for this anomaly. If a sink particle possesses a diameter, which is significant in comparison to the underflow radius, it may protrude into the low centrifugal force portion of the cyclone inner spiral. This spiral also has a high current velocity towards the overflow, and thus may carry the particle to that point. With such solids, industrial recoveries have always exceeded research studies, because the use of larger cyclones eliminated this phenomenon. Data in this paper, therefore, represent a conservative minimum.

size in the range −25 +100 ASTM mesh, volume splits between 15% and 75%, and gravity differences from 0.000 to 0.045.

Estimation of Equivalent Sphere Diameter. These correlations apply strictly to spherical particles. Since most practical applications of this system of solids separation will involve materials of sphericity less than 1, a method must be devised to estimate the diameter of a sphere for use in these correlations which will have the same settling velocity as the particle in question.

A simple method of estimating equivalent sphere diameter is to measure the terminal settling velocity under the influence of gravity of the particle in question in a fluid of known specific gravity and viscosity. By applying these data to Newton's law, a solution can be found for the unknown equivalent sphere diameter.

$$f_D = \frac{4(\rho_s - \rho)gd}{3\rho v_m{}^2} \qquad (9)$$

Equation (9) can be written in the equivalent form:

$$\log f_D = \log Re + \log \frac{4(\rho_s - \rho)\mu g}{3\rho^2 v_m 3} \qquad (10)$$

Equation (10) can be most easily solved graphically on a log-log plot of f_D vs. Re (7) by plotting a line of slope +1 and a f_D intercept of $4(\rho_s - \rho)\mu g/3\rho^2 v_m 3$ at $Re = 1$. The intersection of this straight line and the f_D curve for a sphericity of one will yield the Reynolds number, which can be solved for the equivalent sphere diameter of the particle in question. While this procedure does not yield the equivalent diameter under operating conditions where eddy viscosities are undoubtedly large, the results were found to be sufficiently reliable for preliminary design purposes.

Calculation of Optimum Liquid Gravity, Volume Split, and Feed Composition. The influence of volume split on solids recovery can be vividly portrayed by Figure 11. As particles undergoing no concentrating action will report to the underflow and overflow streams in proportion to the volume split, a more direct scale (% solids to underflow—% slurry to underflow) of solids concentration was devised which gives the per cent in excess of the amount obtained if no concentrating action occurred. The sink curves indicate a maximum at decreasing volume splits as the gravity difference is increased, and the float curves at increasing volume splits. In general, it can be said that the combined separation will be a maximum at that volume split for which the sum of the
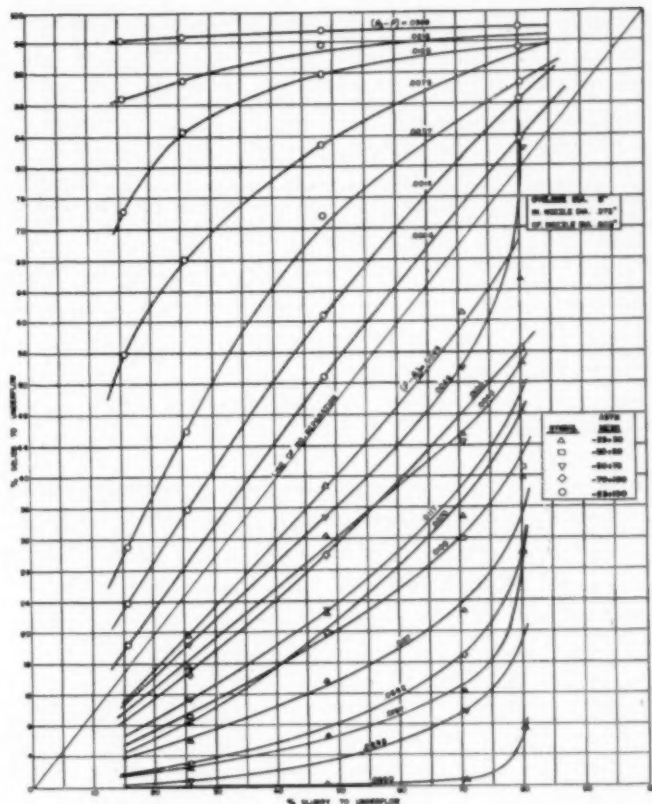

Fig. 8. Plot of % solids to underflow as a function of % slurry to underflow with parameters of particle size and gravity difference.

TABLE 11

ANALYSIS OF VARIANCE SINK DATA

Dependent variable is "% Sink Solids to Underflow"

The following nomenclature is used in this three-factor experiment.

D_1 = −25 + 30 mesh particle size

D_2 = −50 + 70 mesh particle size

G_1 = Specific gravity difference of .0189

G_2 = Specific gravity difference of .0114 to .0115

G_3 = Specific gravity difference of .0057

S_1 = 15.6% Slurry to UF

S_2 = 25.5% Slurry to UF

S_3 = 48.0% Slurry to UF

S_4 = 80.1% Slurry to UF

	D_1			D_2		
	G_1	G_2	G_3	G_1	G_2	G_3
S_1	97.3	71.8	33.1	95.9	77.8	29.2
S_2	98.0	80.3	47.9	96.0	85.9	44.2
S_3	99.0	88.6	72.5	96.3	89.8	75.0
S_4	99.9	97.9	93.7	96.5	91.1	88.1

sink and float ordinates, weighted according to the fraction of sink and float material in the feed is a maximum.

One method of quantitatively fixing the volume split has been indicated. The liquid specific gravity must be specified and the variation of primary cyclone feed composition due to recycle when using cyclones in series must be considered. There are many methods of mathematical approach to maximizing recovery and purity in a cyclone problem. One such method will be considered here. A convenient criterion for optimum separation is

$$
\% \text{ total separation} = 100 \times \left[\frac{\begin{array}{cc} \text{Weight of float} & \text{Weight of sink} \\ \text{material} & + & \text{material} \\ \text{in the overflow} & \text{in the underflow} \end{array}}{\begin{array}{c} \text{Weight of float + sink material} \\ \text{in the feed} \end{array}} \right]
$$

(11)
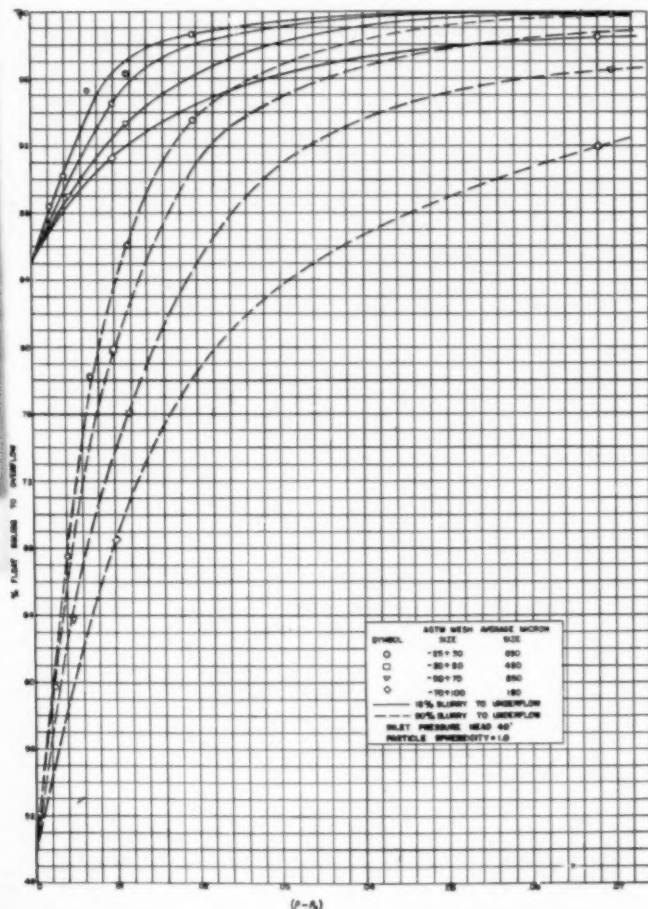
This expression indicates a total separation of 100% when all the float material reports to the overflow and all the sink material reports to the underflow, which clearly is perfect separation.

Using the above criterion, the case where $k = 2$ will be discussed, although it can be extended to higher values. By performing the following six operations, the three variables in question can be set analytically.

1. Assume an inlet composition of float and sink material to the primary cyclone.

2. Assume a value for the liquid specific gravity, thus fixing (ρ sink- ρ liquid) and (ρ liquid- ρ float).
3. Using Figures 9 and 10 and the values given in (1) and (2) above, calculate the per cent total separation for the primary cyclone.
4. Choosing the volume split, which gives the maximum per cent total separation in (3), calculate by trial-and-error volume splits on the secondary cyclones which will yield optimum sink-and-float products and a corresponding recycle composition, which when added to the feed will give the inlet composition assumed in (1).
5. Repeat steps (2) through (4), assuming different liquid specific gravities, thus determining the optimum liquid gravity and volume splits based upon the primary cyclone feed composition assumed in (1).
6. Repeat steps (1) through (5), assuming different inlet feed compositions, thus determining the optimum of all three variables, inlet feed composition, liquid specific gravity, and volume splits.

It must be remembered that quality restrictions on either the final float or sink products (or both) will, in many cases, immediately set the volume splits used in the process. For example, if a low impurity of less than 0.5% float in the sink product is specified, investigation of Figure 6 indicates that low volume splits (at least less than 30%) to the underflow in the sink refining branch of the flow sheet would be required. By this technique, impurity percentages as low as 0.1 or better have been attained in only two stages ($k = 2$).

Industrial Application

To test the validity of the results of this investigation, the problem of separating industrial materials having the properties listed in Table A is presented. A sink product of better than 99.2% purity was demanded with a sink recovery of at least 95%. Investigation of the following data indicates the formidable separation problem presented due to adverse fine particle size distributions, small solids gravity difference and poor shape factors. Reference to Figures 9 and 10 indicates that more than one cyclone would be required to effect the separation specified. Accordingly, a two-stage system with $k = 2$ in Figure 7 was proposed. The procedure outlined


Fig. 9a. Per cent float solids to overflow as a function of gravity difference with parameters of particle size and % slurry to underflow.

TABLE A

	Sink Material Valuable Product	Float Material Refuse Product
Composition	85%	15%
Specific gravity	1.270±.005	1.200±.030
Particle shape	Concave Discs	Needles
Average equivalent sphere, diam. (μ).	340	360
Particle size range (μ)	830 to 0	500 to 0

in the Solids Separation section was used to determine the optimum setting of the liquid specific gravity and the volume splits on the primary cyclone and two secondary cyclones. These calculations also gave estimates of the product recovery and purity to be expected.

To test the above calculations, three cyclones, 3, 4, and 5 in. in diam. were constructed to give capacities and volume splits as recommended with the 5-in. as the first stage and the 4-in. processing the underflow from the first stage. A photograph of the experimental pilot plant is shown in Figure 12. Two tests were then performed on this equipment with the results compared with predicted estimates in Table 13. Test No. 1 was executed under actual operating conditions, where only the recycle streams and the raw feed were discharged into the feed tank. Test No. 2 was performed on a closed system with the recycle and product streams discharging into the feed tank.

Results of both tests indicate good agreement between the calculated and experimental float solids separation, but show appreciable deviations for the sink solids separation. The latter could be partially accounted for by the extremely low sphericity of the sink material and the high concentration of solids in the 4-in. cyclone underflow stream where the largest sink deviations were noted. Probably the predicted and actual difference is due largely to the simplifying assumption of one equivalent spherical diameter for each class of material. Due to the actual large range in particle size, this cannot be precise. A rigorous analytical treatment of this problem would require examining each significant size fraction separately.

The product recovery obtained in Test No. 1, where actual operating conditions were simulated was somewhat lower than obtained in Test No. 2. As an explanation, in Test No. 1, product streams containing approximately 85% of the total 5-in. cyclone feed solids were continually being removed from the system, while the remaining 15% of the solids were recycled. This latter fraction may be composed of materials which, on the average, are more difficult to separate, and tend to build up in the feed at the start of operation, and eventually are reflected in the composition of the product streams. This factor is difficult to account for analytically, and an appropriate safety factor should be used where such a phenomenon is possible.

The comparison of the calculated and experimental pressure drops and volume splits of Test No. 1 shows agreement well within the limits claimed.

Results of the above application are excellent when one considers the ex-
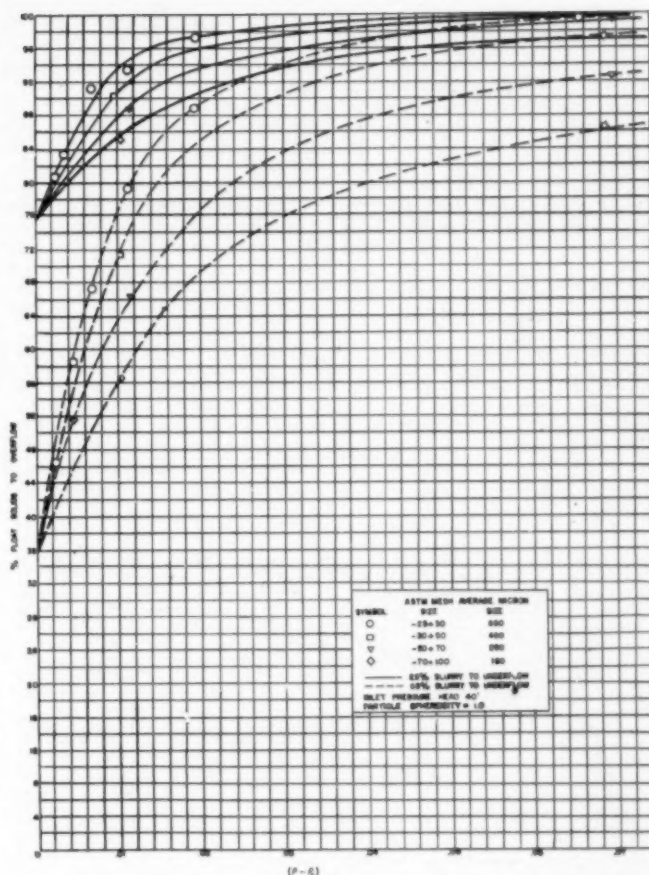

Fig. 9b. Per cent float solids to overflow as a function of gravity difference with parameters of particle size and % slurry to underflow.

TABLE 12

ANALYSIS OF VARIANCE SINK TABLE

Source of Variance	Degrees of Freedom	Sums of Squares	Mean Squares	Components of Variance
S (3)	3	2,620.83	873.61	$\sigma_r^2 + \sigma_{SD}^2 + \sigma_{SG}^2 + \sigma_S^2$
D	1	8.52	8.52	$\sigma_r^2 + \sigma_{SD}^2 + \sigma_{DG}^2 + \sigma_D^2$
G	2	5,642.95	2,821.48	$\sigma_r^2 + \sigma_{SG}^2 + \sigma_{DG}^2 + \sigma_G^2$
S x D	3	33.52	11.30	$\sigma_r^2 + \sigma_{SD}^2$
S x G**	6	2,105.96	360.99	$\sigma_r^2 + \sigma_{SG}^2$
D x G	2	24.24	12.12	$\sigma_r^2 + \sigma_{DG}^2$
Residual	6	42.11	7.02	σ_r^2
Total	23	10,537.93		

*Significant at 5% level

***Significant at 0.1% level

** Due to the large mean square for the S x G interaction, the significance test of this variable is insensitive. Significance of this variable has been established by other tests and will be considered so here.

treme difficulty of separation and that continuous industrial processes on this material to meet specifications had been impossible. The high quality restriction of 0.8% float impurity with 95% recovery of the sink product was easily met. The industrial installation with larger cyclones yielded impurities of no more than 0.2% with recoveries of 98-99%. It might also be added that higher recoveries and product purity could have been obtained by using another refining stage.

Summary

Results of this investigation lead to the following conclusions.

1. Cyclone included angle should be kept as low as possible consistent with head room available.

2. Height of cylindrical section should be at least 6 in.

3. Inlet nozzle angle should allow the inlet stream to descend one inlet nozzle diameter per revolution at the cyclone wall.

4. Distance between the inlet nozzle and top of cyclone must be kept to a minimum consistent with ease of construction.

5. Vertical position of overflow nozzle must be even with the center of the inlet nozzle for volume splits above 50%. For volume splits below 50% the sink solids separation can be improved slightly by extending this nozzle about ⅓ cyclone diameter below the inlet nozzle.

6. Underflow nozzle diameter is dictated by the volume split specified, and can be estimated by Equation (7).

7. Inlet nozzle diameter (b) and overflow nozzle diameter (e) are fixed by the required flow capacity and specified pressure drop as indicated in Equations (1) to (4). The exact values of e and b

must give the product specified here and also have an e/b ratio between 1 and 2.

8. Cyclone diameter in general should be approximately equal to $2 (2b + e)$.

In regard to operating variables, it was established that solids concentration on any stream should be kept to 4%, especially for float material if a high degree of purity is required. Where sphericities approach one, values up to 8% can be tolerated. Larger concentrations can be used at slightly reduced separation efficiencies.

The optimum cyclone pressure drop was found to be approximately 40 ft. of fluid. However, 20 ft. is sufficient for volume splits close to 50%. Larger values can be used to increase capacity, but will have little effect upon increasing recovery.

For cyclones designed and operated as indicated here, the float-and-sink solids separation have been evaluated
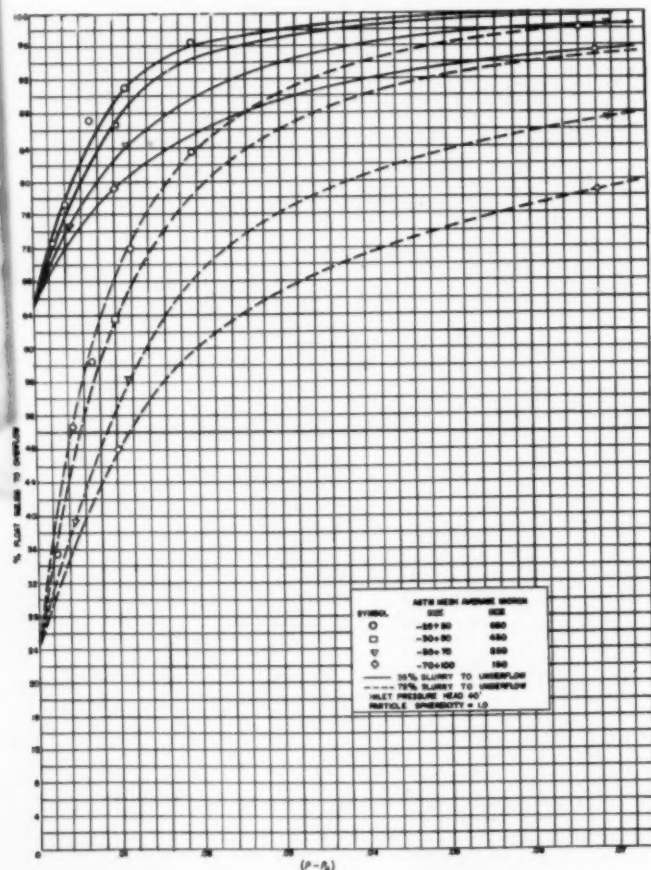

Fig. 9c. Per cent float solids to overflow as a function of gravity difference with parameters of particle size and % slurry to underflow.

Fig. 10. Per cent sink solids to underflow as a function of gravity difference with parameters of % slurry to underflow.
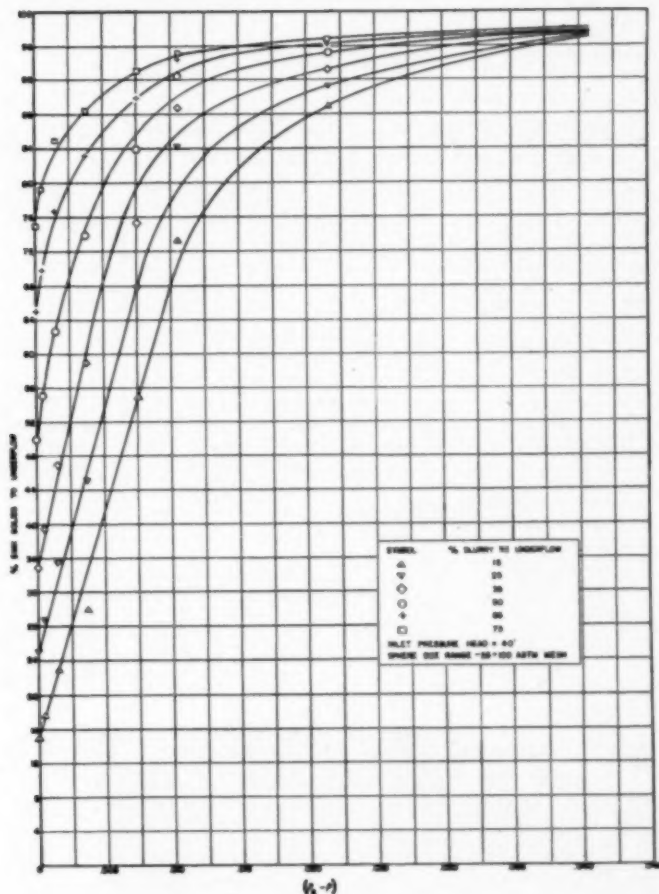
as a function of particle size from −25 to +100 ASTM mesh, volume splits from 15% to 75%, and gravity differences from 0.000 to 0.075 for float material and 0.000 to 0.045 for sink material. These results are presented in Figures 9 and 10 which apply to spherical particles. A method of estimating the equivalent sphere diameter of any shape particle by the application of Newton's law has been outlined.

The effectiveness of the liquid-solid cyclone is uninjured by equal back pressures at the overflow and underflow nozzles, and thus, the above design equations and solids separation data are also applicable to cyclones operated under these conditions. This fact makes possible the operation of cyclones in series without intermediate pumps as shown in Figure 7.

Actual verification of industrial application of this process has been made,

and results agree reasonably well with predicted values calculated from this study. Finally, the economic and process advantages offered by the low cost, high capacity, and separation power of the cyclone have been indicated.

Notation

b = cyclone inlet diam., in.
C, C' = proportionality constant
D_c = cyclone diam., in.
d = particle diam., ft.
e = cyclone overflow diam., in.
E = mathematical constant, 2.718
f_D = friction factor
$$= \frac{4(\rho_s - \rho)gd}{3\rho v_m{}^2}$$
F = cyclone energy loss, feet of fluid
g = gravitational acceleration, ft./(sec.)(sec.)

gal./min. = cyclone feed rate
k = number of stages of separation in series cyclone arrangement
K = cyclone pressure drop constant $= \dfrac{(\text{gal./min.})}{\sqrt{F}(eb)^{0.9}}$
OF refers to cyclone overflow stream
u = cyclone underflow nozzle diam., in.
UF refers to cyclone underflow stream
VS = volume split, % of total cyclone feed volume reporting to underflow
v_m = particle terminal settling velocity, ft./sec.
ρ = fluid specific gravity, g./cc.
ρ_s = solid specific gravity, g./cc.
μ = fluid viscosity, lbs./(ft.-sec.)

TABLE 13

MULTIPLE CYCLONE TESTS

	Test No. 1		Test No. 2	
	Calcu-lated	Experi-mental	Calcu-lated	Experi-mental
5" Inlet Diameter - Inches	0.550	0.550	0.550	0.550
5" Overflow Diameter - Inches	0.844	0.844	0.844	0.844
5" G.P.M.	17.5	17.6	13.4	13.4
4" Inlet Diameter - Inches	0.375	0.375	0.375	0.375
4" Overflow Diameter - Inches	0.550	0.550	0.550	0.550
4" G.P.M.	9.4	10.3	5.8	5.8
3" Inlet Diameter - Inches	0.375	0.375	0.375	0.375
3" Overflow Diameter - Inches	0.364	0.364	0.500	0.500
3" G.P.M.	8.1	7.3	7.6	7.6
Liquid Specific Gravity	1.235	1.235	1.238	1.238
% of Sink Solids to 5" UF	97.5	90.8	96.9	91.1
% of Float Solids to 5" OF	90.0	79.3	95.8	93.3
% of Sink Solids to 4" UF	96.0	61.0	95.8	73.8
% of Float Solids to 4" OF	96.8	91.7	97.3	91.7
% of Sink Solids to 3" UF	97.6	63.9	97.6	89.7
% of Float Solids to 3" OF	89.3	90.4	88.8	87.8
Sink Product Purity %	99.9	99.6	99.9	99.8
Recovery of Sink Material %	99.9	95.2	99.9	98.6
5" Feed Solids Concentration	3.01	3.01	3.00	2.93
5" OF Solids Concentration	1.14	1.28	1.20	1.35
5" UF Solids Concentration	4.33	4.24	4.90	4.99
4" OF Solids Concentration	-	2.33	-	1.98
4" UF Solids Concentration	-	9.54	-	11.75
3" OF Solids Concentration	-	2.11	-	2.79
3" UF Solids Concentration	-	0.73	-	0.66
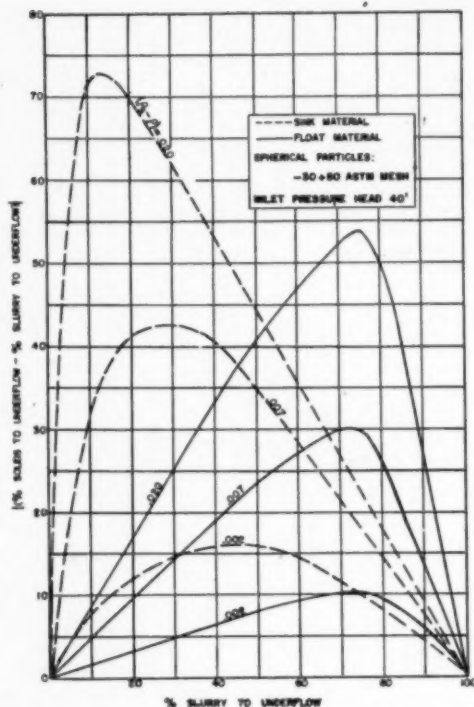
▲ Fig. 11. Absolute difference between % solids and % slurry to underflow as a function of % slurry to underflow.
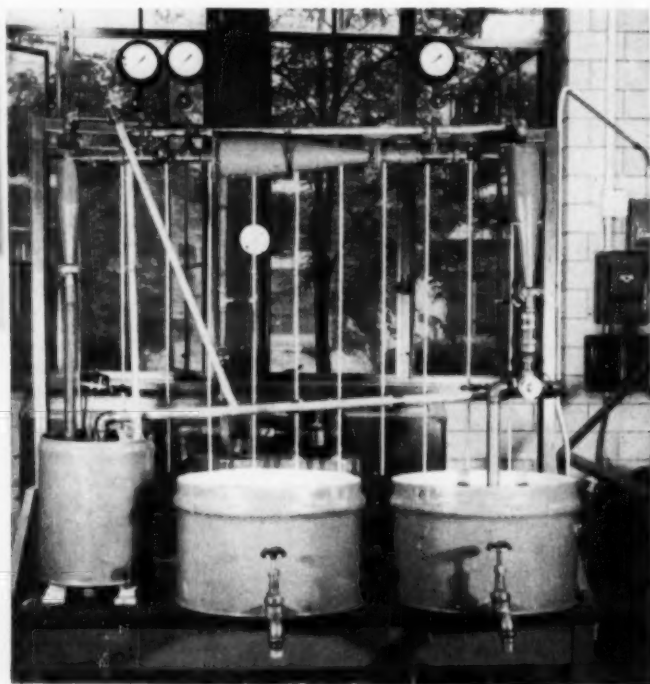
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Fig. 12. Multiple cyclone arrangement.

FLUID FLOW THROUGH PACKED COLUMNS

SABRI ERGUN

Carnegie Institute of Technology†, Pittsburgh, Pennsylvania

The existing information on the flow of fluids through beds of granular solids has been critically reviewed. It has been found that pressure losses are caused by simultaneous kinetic and viscous energy losses, and that the following comprehensive equation is applicable to all types of flow.

$$\frac{\Delta P}{L} g_c = 150 \frac{(1-\epsilon)^2}{\epsilon^3} \frac{\mu U_m}{D_p^2} + 1.75 \frac{1-\epsilon}{\epsilon^3} \frac{G U_m}{D_p}$$

The equation has been examined from the point of view of its dependence upon flow rate, properties of the fluids, and fractional void volume, orientation, size, shape, and surface of the granular solids. Whenever possible, conditions were chosen so that the effect of one variable at a time could be considered. A transformation of the general equation indicates that the Blake-type friction factor has the following form:

$$f_k = 1.75 + 150 \frac{1-\epsilon}{N_{Re}}$$

A new concept of friction factor, f_v, representing the ratio of pressure drop to the viscous energy term is discussed. Experimental results obtained for the purpose of testing the validity of the equation are reported. Numerous other data taken from the literature have been included in the discussions.

THE pressure loss accompanying the flow of fluids through columns packed with granular material has been the subject of theoretical analysis and experimental investigation. The purpose of the present paper is to summarize the existing information, to verify further experimentally a theoretical development presented earlier, and to discuss practical applications of this new approach. The experimental studies have been confined to gas flow through crushed porous solids. This case is the one usually encountered in practice, but is not identical with the case most thoroughly studied by previous investigators, viz., the flow of fluid through beds of nonporous solids, and more particularly, through solids having uniform geometric shapes.

Factors determining the energy loss (pressure drop) in the packed beds are numerous and some of them are not susceptible to complete and exact mathematical analysis. Various workers in the field have made simplifying assumptions or analogies so that they could

† Coal Research Laboratory.

utilize some of the general equations representing the forces exerted by the fluids in motion (molecular, viscous, kinetic, static, etc.) to arrive at a useful expression correlating these factors. A survey of the literature reveals various expressions derived from different assumptions, correlating the particular experimental data obtained with or without some of the data published earlier. These correlations differ in many respects; some are to be used only at low fluid flow rates, while others are applicable only at higher rates. A separate survey of all these various correlations is not included here.

As most authorities agree, the factors to be considered are: (1) rate of fluid flow, (2) viscosity and density of the fluid, (3) closeness and orientation of packing, and (4) size, shape, and surface of the particles. The first two variables concern the fluid, while the last two the solids.

1. Rate of Fluid Flow. It is known that pressure drop through a granular bed is proportional to the fluid velocity at low flow rates, and approximately to the square of the velocity at high rates.

Osborne Reynolds (23) was first to formulate the resistance offered by friction to the motion of the fluid as the sum of two terms, proportional respectively to the first power of the fluid velocity and to the product of the density of the fluid with second power of its velocity:

$$\Delta P/L = aU + b\rho U^2 \qquad (1)$$

where ΔP is the pressure loss along the length L, ρ the density of the fluid, U its linear velocity, and a and b are factors which are functions of the system. A transformation of Equation (1) which yields a linear expression is:

$$\Delta P/LU = a + bG \qquad (2)$$

where ρU has been replaced by G, the mass flow rate. The above two-term pressure-drop equation has been found to be satisfactory over the range of flow rates encountered in packed columns. Lindquist (19), Morcom (20), and Ergun and Orning (7) have plotted $\Delta P/LU$ against G and obtained straight lines as expected from Equation (2). The former two authors have included in their plots factors which pertain to the properties of the system. These factors are important and will be discussed later, but they are irrelevant for the purpose of testing the linearity of Equation (2). As a typical plot, data obtained for gas flow through a bed of crushed porous solids are shown in Figure 1. The experimental results of the present investigation and those mentioned above (7, 19, 20), as well as the data obtained from the literature (3, 22), indicate that the two-term equation accurately expresses the relation between flow rate and pressure drop.

2. Viscosity and Density of Fluid. From Equation (2) it is seen that as the velocity approaches zero as a limit, the ratio of pressure drop to velocity will become constant:

$$\lim_{U \to 0} \frac{\Delta P/L}{U} = a \qquad (3)$$

which is a condition for viscous flow. According to the Poiseuille equation and Darcy's law, the factor a is proportional to the viscosity of the fluid. The other limiting condition is reached at high flow rates when the constant a is negligible in comparison to bG. This is a condition for completely turbulent flow where kinetic energy losses constitute the whole resistance. The effect of density is already contained in G. Equation (2) can be rewritten:

$$\Delta P/L = a'\mu U + b\rho U^2 \qquad (4)$$

where μ is the viscosity of the fluid and a' ($= a/\mu$) is a factor pertaining to the variables of the solids only. The first term of Equation (4) represents viscous energy losses and the second term the kinetic energy losses. The Kozeny equation (14) makes use of the kinetic energy term to represent the pressure drop, while the Blake (2), Burke and Plummer (3), and Chilton and Colburn (5) approach employs the kinetic energy term and compensates the effect of viscous energy losses with a variable friction factor.

3. Closeness (Fractional Void Volume) and Orientation of Packing. Fractional void volume has been one of the most controversial factors in packed systems. Early theoretical treatments were not successful in establishing the dependency of the pressure drop upon fractional void volume. It was Blake who first successfully treated the problem by an approach analogous to that of Stanton and Pannell (25) to pressure drop in circular pipes. Blake obtained the following dimensionless groups:

$$\frac{\Delta P g_c}{L \rho U^2} \frac{D_p}{\;} \frac{\epsilon^3}{1-\epsilon} \text{ and } \frac{D_p \rho U}{\mu(1-\epsilon)}$$

where ϵ is the fractional void volume, g_c the gravitational constant, and D_p the diameter of the solid particles. The first of these groups is recognized as the modified friction factor and the second as the modified Reynolds number. Blake suggested that the former of these groups be plotted against the latter. Since both dimensionless groups contain the fractional void volume, it can be deduced that pressure drop is not a function of a single group alone.

The failure of the earlier attempts to arrive at a useful expression can be attributed to the want of recognition of the fact that pressure drop is caused by simultaneous kinetic and viscous energy losses.
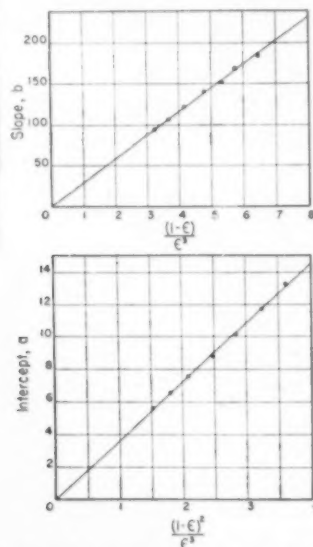
Fig. 2. Dependence of viscous and kinetic energy losses on fractional void volume, Equations (7) and (8). Intercepts and slopes are obtained from data of Figure 1 by method of least squares.
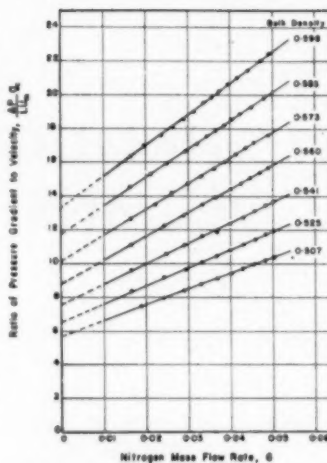
Fig. 1. Typical plots of the linear form of pressure-drop equation for a system packed to different fractional void volumes, Equation (2). Nitrogen flow through 16-20 mesh high temperature oven coke. Particle density = 1.06 g./cc. Cross-sectional area of tube = 7.24 sq.cm. Exit at 724 mm. Hg. and 21° C.

Theoretical considerations of later workers (3, 7) indicate that dependency of each energy loss upon fractional void volume is different. Burke and Plummer proposed the theory that the total resistance of the packed bed can be treated as the sum of the separate resistances of the individual particles in it. Accordingly, viscous energy loss was found to be proportional to $(1-\epsilon)/\epsilon^2$ and kinetic loss to $(1-\epsilon)/\epsilon^3$. The authors, however, failed to recognize the additive nature of these losses and correlated the pressure drop by the use of dimensionless groups similar to those of Blake. For viscous flow, Kozeny (14) arrived at an equation widely used later (4, 10, 11, 13, 15, 26) by assuming that the granular bed is equivalent to a group of similar parallel channels. The derived dependency upon fractional void volume was $(1-\epsilon)^2/\epsilon^3$. This factor is different by a fraction $(1-\epsilon)/\epsilon$ from the factor derived by Burke for viscous flow. Fair and Hatch (10), Carman (4), Lea and Nurse (15), Fowler and Hertel (11), and others (6, 13, 17, 26) verified the Kozeny factor experimentally. For a general correlation valid at all flow rates, however, Carman recommended the plot of the dimensionless groups of Blake. Recently, Leva (18) and Morse (21) also adopted Blake's procedure in presenting the pressure drop data in fixed beds. Leva, et al. (18) stated that the pressure drop was proportional to $(1-\epsilon)^2/\epsilon^3$ at lower flow rates and to $(1-\epsilon)/\epsilon^3$ at higher flow rates.

Carman noted that at low fluid-flow rates the method of Blake leads to the Kozeny equation, hence to the factor $(1-\epsilon)^2/\epsilon^3$:

$$\frac{\Delta P g_c}{L} = k_1 \frac{(1-\epsilon)^2}{\epsilon^3} \frac{\mu U}{D_p^2} \tag{5}$$

On the other hand, at high flow rates Blake's method gives rise to the equation of Burke and Plummer for turbulent flow:

$$\frac{\Delta P g_c}{L} = k_2 \frac{1-\epsilon}{\epsilon^3} \frac{\rho U^2}{D_p} \tag{6}$$

the factor involving the fractional void volume being $(1-\epsilon)/\epsilon^3$. This range of the plot of Blake has generally been overlooked.

Based on the theory of Reynolds for resistance to fluid flow and the method of Kozeny, a general equation was developed by Ergun and Orning for pressure drop through fixed beds. In summary the following conclusions can be drawn from their work:

1. Total energy losses in fixed beds can be treated as the sum of viscous and kinetic energy losses.

2. Viscous energy losses are proportional to $(1-\epsilon)^2/\epsilon^3$ and the kinetic energy losses to $(1-\epsilon)/\epsilon^3$. Since a and b of Equation (4) represent the coefficients of viscous and kinetic energy losses, respectively, it is expected that a be proportional to $(1-\epsilon)^2/\epsilon^3$ and b to $(1-\epsilon)/\epsilon^3$ in order for the theory to be valid. Although the above authors have correlated their data successfully, single systems have not been thoroughly examined at various fractional void volumes. One of the aims of the present work has been to investigate the single systems at various packing densities. A known amount of solids was packed 6 to 20 different bulk densities each resulting in a different fractional void volume. For each packing the coefficients a and b of Equation (2) were determined from pressure drop and flow rate measurements (Fig. 1). Figures 2 and 3 show typical plots of a against $(1-\epsilon)^2/\epsilon^3$ and b against $(1-\epsilon)/\epsilon^3$ obtained from Figure 1. Such plots yield straight lines each passing through the origin. The graphical representation is simple, yet most effective in the investigation of the function of fractional void volume. A similar procedure has been adopted recently by Arthur, et al. (1) in testing the validity of the Kozeny equation and by Ergun (8) in connection with particle density determinations for porous solids. It is of interest also to note that the two extreme ranges of the Blake plot lead to the terms of the general equation proposed by Ergun and Orning. The proportionalities can be expressed in the formulae:

$$a = a'' \frac{(1-\epsilon)^2}{\epsilon^3} \tag{7}$$

$$b = b'' \frac{1-\epsilon}{\epsilon^3} \tag{8}$$

where a'' and b'' are factors of proportion-
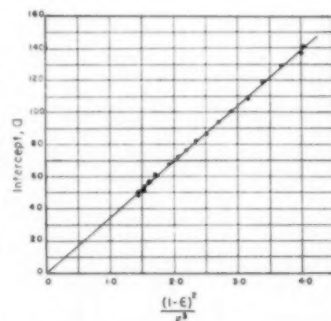
Fig. 3. Dependence of viscous energy losses on fractional void volume, Equation (7). Data obtained for nitrogen flow through 50-60 mesh Eagle coke. Particle density = 1.27 g./cc. Cross-sectional area of the tube = 7.24 sq.cm. Exit gas at 740 mm. Hg. and 23° C.

ality. Their substitution into Equation (2) yields:

$$\frac{\Delta P}{L} = a'' \frac{(1-\epsilon)^2}{\epsilon^3} U + b'' \frac{1-\epsilon}{\epsilon^3} \rho U^2 \tag{9}$$

A rearrangement of Equation (9) leads to:

$$\frac{\Delta P}{LU} \frac{\epsilon^3}{(1-\epsilon)^2} = a'' + b'' \frac{G}{1-\epsilon} \tag{10}$$

Equation (10) makes it possible to group all data of Figure 1 on a single line by plotting

$$\frac{\Delta P}{LU} \frac{\epsilon^3}{(1-\epsilon)^2}$$

against $G/(1-\epsilon)$. This is demonstrated in Figure 4.

Up to this point the aim has been to formulate the effect of fractional void volume in fixed beds, and the effect of orientation was not included. The orientation of the randomly packed beds is not susceptible to exact mathematical formulation. This is especially true if the particles have odd shapes and are not negligible in size compared with the diameter of the container. Furnas (12) has treated the subject at length and introduced the concept of "normal packing" which was obtained by a standard procedure. In the present investigation, however, such a concept had to be abandoned. The problem was to pack a known amount of solids to various bulk densities; yet each packing had to be uniform and reproducible.

This was accomplished by admitting gas below the supporting grid after the solids were poured in. The gas rate was sufficient to keep the bed in an expanded state and the use of a vibrator attached to the tube assured the uniformity of the packing. By varying the rate of upward gas flow, the bulk density could be varied from the tightest possible to the lousest stable packing. For crushed material the most tightly packed bed having a height of 30 cm. could easily be expanded by 6 to 7 cm. When the desired packing density was attained, the vibrator was disconnected and the gas flow cut off. The bed then was ready for pressure drop and flow rate measurements. Highly reproducible packings can be obtained by this method, and more important, the particles are believed to be oriented by the gas flowing upward. This is evidenced by the existence of a theoretical relationship (7), verified experimentally, between the bed expansion and the flow rate. A further evidence for particle orientation was found in the fact that the most tightly packed beds have been obtained by slowly reducing the rate of upward gas flow to an initially expanded bed while subjecting it to vibration.

It will be evident on inspection of the form of Equation (9) that the estimation of fractional void volume is important, particularly since it enters to second- and third-power terms and is in many cases difficult to measure directly. Whenever the particle density and the total weight of the granular material filling a given volume are known, ϵ may be readily calculated. But the particle density of crushed porous materials is not readily known and its determination has presented a problem which was much discussed. Fractional void volumes were usually calculated by the use of apparent specific gravities which were determined by various procedures. Use of such values for ϵ in the pressure-drop equations necessitated the introduction of correction factors. This often caused the workers to doubt the validity of the factors describing the dependence of pressure drop

upon ϵ and to seek new correlations. However, this was believed to be unwarranted (8) since the determination of pressure drop through beds of porous particles hinges upon the evaluation of the particle density. Therefore, a gas flow method was developed (8) for the determination of the particle density of porous granules. The method was checked by the densities obtained for nonporous solids and the agreement was good. Use of the particle densities of coke obtained by the method described, in the determination of fractional void volume and hence in the pressure drop equation, resulted in excellent agreements.

4. Size, Shape and Surface of the Particles. The effect of the particle size and shape is best analyzed in the light of theoretical implications of the Blake plot. The identity between the two extreme ranges of the Blake plot and the theoretical equations developed respectively by Kozeny and Burke for viscous- and turbulent-flow ranges has already been shown. Also, it has been pointed out that these two expressions constituted the following general equation developed by Ergun and Orning (7):

$$\Delta P g_c / L = 2\alpha \mu S_v^2 U_m (1-\epsilon)^2 / \epsilon^3 + (\beta/8) G U_m S_v (1-\epsilon) / \epsilon^3 \tag{11}$$

where α and β are statistical constants, g_c is the gravitational constant, and S_v is the specific surface of solids, i.e., surface of the solids per unit volume of the solids. Instead of specific surface, S_v, surface per unit packed volume, S, has been employed by some workers. Since the latter quantity involves the fractional void volume, use of specific surface has been preferred in the present work. The relation between the two quantities is expressed by

$$S = (1-\epsilon) S_v$$

Equation (11) involves the concept of "mean hydraulic radius" in its theoretical development (7). Its validity has been tested with spheres, cylinders, tablets, nodules, round sand and crushed materials (glass, coke, coal, etc.) and found to be satisfactory. The experiments have not been extended to include solids having holes and other special shapes. For those

Fig. 4. A general plot for a single system packed to different fractional void volumes. Data of Figure 1 are grouped on a single straight line representing Equation (10).

cases the concept of specific surface was believed to be not applicable by Burke who suggested compensation by empirical factors in connection with the use of the Blake plot.

Determination of specific surface involves the measurement of the solid surface area as well as that of solid volume and presents no problem for uniform geometric shapes. For irregular solids, especially for porous materials, however, surface area determination becomes involved. The surface of porous materials is necessarily full of holes and projections. Different surface areas are usually defined in connection with porous materials, viz., total surface area (including that of pores), external visible surface area, geometric surface area, etc. A geometric surface, as distinct from external visible surface, may be visualized as the surface of an impervious envelope surrounding the body in an aerodynamic sense. Irregularities and striae on the surface would not be taken into full account in a geometric surface area in contrast to external surface area. Whether the value of the total, external or geometric surface area is desired will depend on the purpose for which it is to be used. Geometric surface area is believed (9) to be the relevant one in connection with the pressure drop in packed columns. This is made evident by the close agreement between the surface areas determined by gas-flow methods and those by microscopic and light extinction methods. Inasmuch as the surface roughness affects both the geometric surface area and the particle density, the determination of its influence upon pressure drop lies in the evaluation of the effective values of these quantities.

It has been customary to use a characteristic dimension to represent the particle size in pressure-drop calculations. The characteristic dimension generally used is the diameter of a sphere having the specific surface, S_v, which is expressed by

$$D_p = \frac{6}{S_v}$$

Substitution of D_p into Equation (11) yields:

$$\frac{\Delta P g_c}{L} = k_1 \frac{(1-\epsilon)^2}{\epsilon^3} \frac{\mu U_m}{D_p^2} + k_2 \frac{1-\epsilon}{\epsilon^3} \frac{G U_m}{D_p} \tag{12}$$

where $k_1 = 72 \, \alpha$ and $k_2 = 3/4 \, \beta$. A linear form of Equation (12) is:

$$\frac{\Delta P g_c}{L} \frac{D_p^2}{\mu U_m} \frac{\epsilon^3}{(1-\epsilon)^2} = k_1 + k_2 \frac{N_{Re}}{1-\epsilon} \tag{13}$$

where

$$N_{Re} = \frac{D_p G}{\mu}$$

The left-hand side of Equation (13) is the ratio of pressure drop to the viscous energy term and will be designated by f_v.

$$\frac{\Delta P g_c}{L} \frac{D_p^2}{\mu U_m} \frac{\epsilon^3}{(1-\epsilon)^2} = f_v \tag{13a}$$

$$f_v = k_1 + k_2 \frac{N_{Re}}{1-\epsilon} \tag{13b}$$

According to Equation (13) a linear relationship exists between f_v and $N_{Re}/1-\epsilon$. Data of the present investigation and those presented earlier have been treated accordingly, and the coefficients k_1 and k_2 have been determined by the method of least squares. The values obtained are $k_1 = 150$ and $k_2 = 1.75$ representing 640 experiments. Data involved various-sized spheres, sand, pulverized coke, and the following gases: CO_2, N_2, CH_4 and H_2. Once the constants k_1 and k_2 were obtained it was
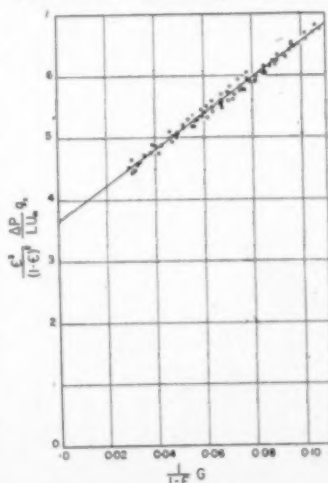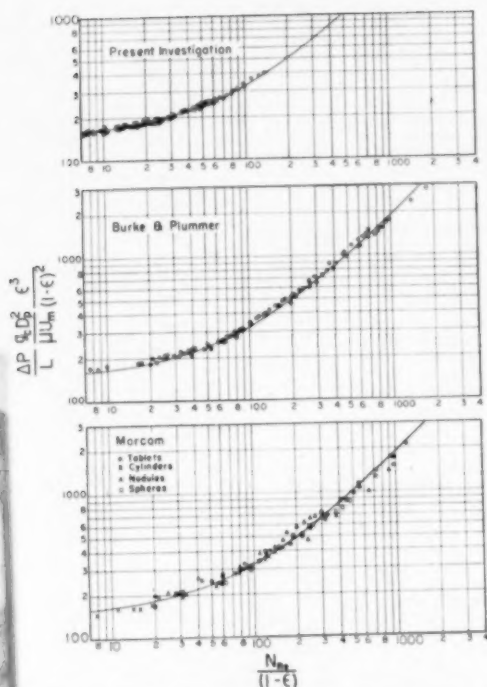
Fig. 5. A general graphical representation of pressure drop applicable to both viscous and turbulent flows for systems considered. Solid lines in all three cases are drawn according to Equation (13c) and are linear on arithmetic scale. The ordinate is represented by f_v, Equation (13a).


Fig. 7. Graphical representation of pressure drop in fixed beds. Data of Figure 5 are replotted. In all three cases solid lines are identical and are drawn according to Equation (14b). The ordinate is represented by f_k, Equation (14a).

Fig. 6. A comprehensive graphical representation of pressure drop in packed columns. Solid line represents linear Equation (13c).

○ Present investigation   △ Morcom
✕ Burke and Plummer   □ Oman and Watson.

possible to construct the general equation. The results are shown on the top of Figure 5. To be able to include a wider range of data, a logarithmic scale has been used which results in a curve for the straight line of Equation (13). Data of Burke and Plummer and those of Morcom are also shown in Figure 5. In all three cases the solid lines are identical and are drawn according to the following equation:

$$f_v = 150 + 1.75 \frac{N_{Re}}{1-\epsilon} \qquad (13c)$$

Data shown in Figure 5 and some additional data obtained from the literature covering wider ranges of flow rate are included in Figure 6, together with the asymptotes of the resulting curve on the logarithmic scale. Again the solid line represents Equation (13c).

A different form of Equation (12) is represented by:

$$\frac{\Delta P g_c}{L} \frac{D_p}{G U_m} \frac{\epsilon^3}{1-\epsilon} = k_1 \frac{1-\epsilon}{N_{Re}} + k_2 \qquad (14)$$

The left-hand side of Equation (14) is the ratio of total energy losses to the term representing kinetic energy losses and will be designated by f_k

$$\frac{\Delta P g_c}{L} \frac{D_p}{G U_m} \frac{\epsilon^3}{1-\epsilon} = f_k \qquad (14a)$$

$$f_k = 150 \frac{1-\epsilon}{N_{Re}} + 1.75 \qquad (14b)$$

f_a is similar to the friction factor more commonly used and is identical with the dimensionless group of Blake. It will be noted that Burke and Plummer plotted essentially f_a vs. $(1 - \epsilon)/N_{Re}$, which plot, according to Equation (14), should yield a straight line on an arithmetic scale. The authors apparently failed to recognize this fact. The best curve drawn through the experimental points on an arithmetic scale does not differ markedly from the line representing Equation (14b). The scatter to be seen on the plot of Burke and Plummer was largely due to the systems involving mixtures and those for which the ratio of tube diameter to particle size was less than 10. These systems have been omitted in Figure 5. It has been customary, however, to plot f_a against $N_{Re}/(1 - \epsilon)$ instead of the inverse of the last variable. This type of plot is the one suggested by Blake and adopted by Carman, Morse and others. Figure 7 shows f_a plotted vs. $N_{Re}/(1 - \epsilon)$ for the data already presented in Figure 5. Figure 8 is a more comprehensive presentation. The solid lines are drawn according to Equation (14b). A comparison of Figure 6 with 8 is analogous to that of f_v with f_a. Both plots are capable of presenting the data. However, f_v has a big advantage over f_a in that it is a linear function of the modified Reynolds number, viz., $N_{Re}/(1 - \epsilon)$. The curve of Figure 6 is a straight line on an arithmetic scale. On the other hand, f_a, which has been used almost exclusively, is an inverse function. A comparison of various empirical representations with Equation (12) is to be seen in Figure 9.

The foregoing treatment so far has been confined to studying the factors involved in the pressure loss in packed beds and to analyzing experimentally the theoretical developments presented earlier. It is only proper that the equations presented are also analyzed briefly from the standpoint of pure fluid dynamics. Fortunately, the equations lend themselves for such analyses. By definition:

$$D_p = 6/S_v \qquad (15a)$$

and

$$S_v = S_t/AL(1 - \epsilon) \qquad (15b)$$

where S_t = total geometric surface area of the solids and A = cross-sectional area of the empty column. The total force exerted by the fluid on the solids = $\Delta P g_c A \epsilon$, therefore the tractive force per unit solid surface area, usually referred to as the shear stress, τ, is expressed by:

$$\tau = \Delta P g_c A \epsilon / S_t \qquad (15c)$$

The ratio of the volume occupied by the fluid in the bed, $AL\epsilon$, to the surface area it sweeps, S_t, is the hydraulic radius, r_h,

$$r_h = AL\epsilon/S_t \qquad (15d)$$

The actual average velocity of the fluid in the bed is obtained from the ratio of the superficial fluid velocity to the fractional voids,

$$u = U/\epsilon \qquad (15e)$$

Substitution of Equations (15a-e) into Equation (13a) gives

$$f_v = 36 \frac{\tau r_h}{\mu u} \qquad (16)$$

and into Equation (14a) gives

$$f_b = 6 \frac{\tau}{\rho u^2} . \qquad (17)$$

Similarly proper substitution will yield

$$\frac{N_{Re}}{1 - \epsilon} = \frac{6 \rho u r_h}{\mu} \qquad (18)$$

Therefore, Equations (13) and (14) respectively will become:

$$36 \frac{\tau r_h}{\mu u} = 150 + 1.75 \frac{6 \rho u r_h}{\mu} \qquad (19)$$

and

$$6 \frac{\tau}{\rho u^2} = 150 \frac{\mu}{6 \rho u r_h} + 1.75 \qquad (20)$$

It is seen that these transformations employing the absolute values of shear stress, fluid density, and velocity eliminate the fractional void volume. The terms involved in Equations (16-20) are well known in the fields of hydro- and aerodynamics. Other forms of dependences upon ϵ ascribed to a general equation, as encountered in the literature, would not lead to complete elimination of the fractional void volume upon transformation to these fundamental variables.

The theoretical significances of the constants k_1 and k_2 have been omitted in the foregoing treatment. The former of these constants is discussed by Carman and Lea and Nurse (15) in connection with the Kozeny equation. As a result of comparison of various systems involving different fractional void volumes, Lea and Nurse (16) concluded that $\epsilon (= k_1/72)$ was not a constant but

varied with the fractional void volume. Whether or not k_1 is a constant is to be decided on inspection of the lower end of Figure 6 and the upper end of Figure 8 where viscous energy losses are dominant. However, the inherent inaccuracies involved in the measurements of specific surface, fractional void volume, etc., must be borne in mind. In the present work, moreover, single systems were investigated at different fractional void volumes and no evidence of variance of k_1 with ϵ was found. This point is clearly supported by the proportionality of a to $(1 - \epsilon)^2/\epsilon^3$ as to be seen from Figures 2 and 3, and similar other graphical representations (1, 8, 9). The factor $k_2 (= 3/4\beta)$ is subject to treatment similar to that of k_1 (7, 8, 9).

Summary

The laws of fluid flow through granular beds have several aspects of practical consequence. They generally find use in correlating the rate of mass and heat transfer to and from moving fluids (24). The extension of such relationships to packed columns will require formulation of the laws of fluid flow through granular beds. Empirical correlations are generally useful for the particular purpose for which they are made, but may not shed light for a different purpose. For the sake of clarity in the application and use of the data obtained in packed columns, it seemed desirable to develop expressions (Equation (12)) in a comprehensive form applicable to all types of flow. In doing so the theoretical developments, as well as the empirical approaches, have been considered and the following conclusions have been drawn:

1. Total energy loss in fixed beds can
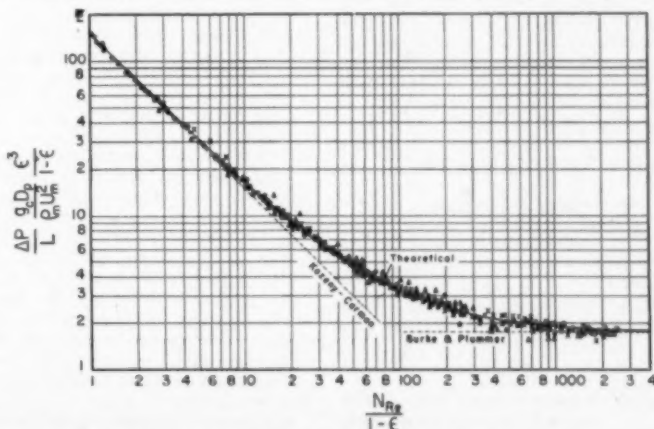
Fig. 8. A comprehensive plot of pressure drop in fixed beds. Data of Figure 6 are replotted. This type of plot is identical with that of Blake. Solid line is drawn according to Equation (14b).
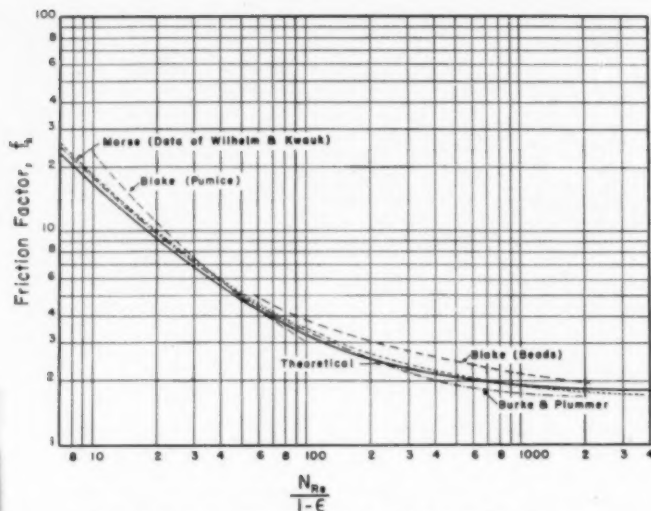
Fig. 9. Comparison of various empirical representations with Equation (12).

be treated as the sum of viscous and kinetic energy losses.

2. Viscous energy losses per unit length are expressed by the first term of Equation (12):

$$150 \frac{(1-\epsilon)^2}{\epsilon^3} \frac{\mu U_m}{D_p{}^2}$$

and the kinetic energy losses by the second term:

$$1.75 \frac{1-\epsilon}{\epsilon^3} \frac{\rho_m U_m{}^2}{D_p}$$

3. For any set of data the relative amounts of viscous and kinetic energy losses can be obtained from either Equation (13) or (14).

4. A new form of friction factor, f_v, representing the ratio of pressure drop to the viscous energy term has been given (Equation 13c) and should have advantages over the conventional type of friction factor.

5. A linear equation has been shown to represent the conventional type of friction factor, viz., the ratio of pressure drop to energy term representing kinetic losses (Equation 14b).

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Notation

a, a', a'' = coefficients in Equations (1), (4), and (7), respectively
A = cross-sectional area of the empty column
b, b'' = coefficients in Equations (1) and (8), respectively
D_p = effective diameter of particles as defined by Equation (15a)
f_v = friction factor, which represents the ratio of pressure loss to viscous energy loss and which is linear with mass flow rate, defined by Equation (13a)
f_k = friction factor, identical with the dimensionless group of Blake, defined by Equation (14a)
g_c = gravitational constant
G = mass-flow rate of fluid, $G = \rho U$
k_1 = coefficient of the viscous energy term in Equation (12); $k_1 = 150$
k_2 = coefficient of the kinetic energy term in Equation (12); $k_2 = 1.75$
L = height of bed
N_{Re} = Reynolds number, $N_{Re} = D_p G / \mu$
P = pressure loss, force units
r_h = hydraulic radius of packed bed, defined by Equation (15d)
S = surface of solids per unit volume of the bed
S_t = total surface area of the solids in the bed
S_v = specific surface, surface of solids per unit volume of solids
u = actual velocity of fluid in the bed
U = superficial fluid velocity based on empty column cross section

U_m = superficial fluid velocity measured at average pressure
α = coefficient of viscous energy term in Equation (11)
β = coefficient of kinetic energy term in Equation (11)
ϵ = fractional void volume in bed
μ = absolute viscosity of fluid
ρ = density of fluid
τ = average shear stress, defined by Equation (15c)

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APPLICATIONS OF FLUID MECHANICS AND SIMILITUDE TO SCALE-UP PROBLEMS

PART II

J. H. RUSHTON

Illinois Institute of Technology, Chicago, Illinois

A brief review of the principles of dynamic similitude is given. Basic concepts of fluid mechanics are used to develop relations between fluid motion, equipment size, and fluid properties that may apply to chemical engineering work. A general method is given whereby the requirements for dynamic similitude for any flowing system can be determined. Examples are given showing how these principles can be used in pilot plant models to obtain scale-up data for operations involving resistance to fluid flow, discharge of liquids from tanks, blending of liquids by a mixer, control of forced vortexes, dissolving of solids during mixing, and absorption and desorption of gases in moving liquids. Suggestions are made for applying the principles to any type of operation involving mass transfer in a liquid, and to other flow operations such as fluidized systems and suspensions.

Applications

Pilot plant operations may be thought of as of two types; those involving the kinematic properties such as viscosity and weight, and those which in addition to the kinematic properties are affected by vapor pressure, solubility, equilibrium, conductivity, and the like. The first type deals with fluid mechanics only, and can be illustrated by examples of fluid flow and certain mixing operations. The second type deals also with chemical reactions and concentrations, and includes such operations as gas absorption and extraction.

Typically Fluid Mechanical. The resistance of flow of fluids through equipment such as pipe lines and heat exchanges can be determined by model studies. The familiar Fanning friction factor and other similar relations are of common knowledge. In these systems it has been shown that the inertia group and the Reynolds number are sufficient to define dynamic similarity when all linear ratios are constant. Therefore, the resistance to flow measured in a model can be projected to the resistance in any larger geometrically similar sys-

Pt. I of this paper was run in the January issue.

tem, and pumps and pipelines can be sized with accuracy. In such systems where there is no free liquid surface and where the fluid is continuous and incompressible, the Froude, Weber, and Cauchy parameters do not apply, and the Reynolds number and the inertia group alone control. A liquid of any viscosity and density can be used in the model to determine the relationship of the inertia group to the Reynolds number, and the results will apply to any other liquid in scale-up by using Equations (1)-(12).

The blending of miscible liquids is a mixing operation often carried out under conditions represented by curve *ABCD* of Figure 1. Normally the operations are carried out under conditions equivalent to the *CD* part of the curve, using side-entering propellers, properly off-centered, or other types of impellers using baffles. Viscous forces do not exert an influence. Under these conditions there will not be a vortex in the surface of the liquid, and weight or gravity forces will not play a part. A pilot plant model can, therefore, be constructed, and the time and power necessary to achieve a desired blend for a given set of feed conditions can be found. These conditions can be projected to a large size tank by keeping the inertia group constant, geometric

similarity and equal liquid flow velocities.

The following example is taken from actual operating data in small and large tanks: A 6-in. diam. square pitch three-blade marine-type propeller operating in a side-entering properly off-centered position in a 15-ft. diam. vertical axis cylindrical tank, was found to blend two gasolines in 40 min. when running at a speed of 1680 rev./min. What size mixer and power are required to blend the two gasolines in the same length time in a 60-ft. diam. tank?

The scale-up will be made on the basis of equal inertia groups, geometric similarity, and equal flow velocities at corresponding points.

All linear dimensions will increase by the ratio of tank size or $60/15 = 4$. Liquid depth will be four times that in the smaller tank; the propeller will be a geometrically similar one 2 ft. in diameter. Liquids are the same. Convert force to power P by $FL/T = P$, then the inertia group may be written $PT^3/\rho L^5$

$$\frac{P_1 T_1^3}{\rho_1 L_1^5} = \frac{P_2 T_2^3}{\rho_2 L_2^5}$$

$$\frac{P_2}{P_1} = \left(\frac{T_1}{T_2}\right)^3 \left(\frac{L_2}{L_1}\right)^5$$

since time occurrences (and velocities) are to be constant $T_1 = 0.25 T_2$ (see line one, Table 2)

then

$$\frac{P_2}{P_1} = (0.25)^3 (4)^5$$

or

$$P_2 = 16 \, P_1$$

Actually, the power required by the model is 0.768 hp., thus the power required by the 24-in. propeller is 16 (0.768) = 12.5 hp. The rotational

speed of the 24-in. propeller is determined from propeller characteristics and is 420 rev./min. for 12.5 hp. Operating results confirmed the scale-up.

A different speed could, of course, be used and the same flow pattern would result, but the blending time would vary. It would then be necessary to know the relation between blending time and speed of rotation from the model, and scale-up made for the different speed condition.

It has been shown elsewhere (16) that when a forced vortex is formed by means of a rotating mixing impeller, a curve like *ABE* (Fig. 1), will result, and at high Reynolds numbers the Froude number is important. To reproduce a vortex geometrically similar in another size vessel, Equation (13) must be satisfied. The same liquid cannot be used in another sized vessel. Equation (13) requires that as size is increased the kinematic viscosity of the liquid must be greater if a similar vortex is to be formed. Figure 2 illustrates this case and shows a cross section of forced vortexes under conditions where similarity is and is not present in systems of two different sizes.

When liquids are withdrawn from tanks through pipes in the bottom, a vortex will form due to weight (or gravity) and viscous forces. The following example will show the use of the similitude relations to set up a pilot model for the case of removing liquid from a storage tank.

A 90-ft. diam. light oil storage tank is to be built and a draw-off pipe 18 in. in diameter is to be placed in the bottom of the tank, 6 ft. from the side wall, and extending vertically from the tank bottom to a height of 18 in. When oil is withdrawn and as the liquid level drops, a vortex will form above the outlet. Both the Reynolds and Froude parameters will be necessary to characterize the flow. If the vortex is allowed to extend to the bottom of the outlet line, air will be drawn into the oil line, and this is to be avoided. At what level of liquid in the tank should the flow be stopped to avoid air entrainment for a given draw-off rate? A small model can be built to determine this for the large tank. The model requirements are determiend as follows:

A piece of 0.45-in. I.D. tubing is available for a draw-off tube. Since the tank diameter is to be 90/1.5, or 60 times the draw-off tube size, the model should be 60(0.45), or 27 in. in diameter, and its height arranged accordingly. The scale of the large tank is $18/0.45 = 40$ times that of the model. The draw-off tube should be placed 6/40, or 0.15 ft. from the side of the model, and the opening should be 0.45 in. above the bottom of the model. Since both the Reynolds and Froude numbers must remain constant over this scale ratio of 40, it is necessary that Equation (13) must apply. Therefore, it is evident that the oil to be used in the large tank cannot be used in the model. Rather, a much more viscous oil must be used in the model.

From Equation (13) $v_r = 40^{3/2} = 305$. Thus a liquid whose kinematic viscosity is 305 times that to be handled in

the large tank should be used in the model. With these dimensions and liquid properties, data from the pilot model can be scaled up by either the Reynolds or Froude number.

Assuming that the large tank is to have a drawn-off rate of 2400 gal./min., the quantity of discharge is equal to the velocity times area, or $Q = uL^2$.

From the Froude scale-up relation (Table 2)

$$u_r = \sqrt{L_r},$$

and then

$$Q_r = u_r L_r^2, \ Q_r = L_r^{5/2} \tag{24}$$

Thus

$$Q = 40^{5/2} = 10,000$$

and

$$Q_2 = \frac{2400}{10,000} = 0.24 \text{ gal./min.,}$$

the discharge rate to be used in the model. If, at this rate, air is drawn into the outlet when the liquid level at a given point at the model wall is 0.8 in. above the bottom, then the level of the liquid at a corresponding position in the large tank must be 0.8(40), or 32 in. Or, this level would be 32-18, or 14 in. above the discharge opening. If the same liquid were used in the model as to be used in the large tank, the level at which air would be induced would be lower, hence when scaled up to the large tank the level would be too low and air would be induced at a higher level than supposed. It should be noted, however, that since the ratio of tank diameter to draw off tube diameter is large (60 to 1) any effect of a small change in this ratio should not be of great importance, hence the data might reasonably be applied to tanks of say 75 to 100 ft. in diameter. Similar reasoning would allow small variations in the model tank diameter.

Operations Involving Mass Transfer

Many absorption, desorption, extraction and solubility operations are affected by agitation—or fluid motion. There are many references to the beneficial effect of mixing or other methods of agitation on such operations, but few data can be found where the effect of size and similarity have been studied.

One study of gas absorption reported by Hutchinson and Sherwood (9) shows the effect of agitation of the liquid phase behind the liquid-gas interface, for a number of gases. Only one small size vessel and mixing impeller was used, but data were obtained for a change in impeller speed. A logarithmic plot of the absorption coefficient and impeller speed showed that the coefficient was constant at very low speeds,

but that a constant positive slope was obtained when speed was increased in the higher speed ranges. It is evident that normal rates of diffusion were controlling the coefficient in the liquid at low stirring speeds, but that at higher speeds the forced fluid motion caused distribution of the solute at a greater rate than diffusion. If the same fluid motion could be achieved in a vessel of larger size, the data should be capable of reproduction in this larger system. It is inferred from a description of the apparatus that there may have been swirl and vortex in the liquid, and if this were true, then it is not possible to use these data for scale-up because of Equation (13). This work was undertaken to show the effect of liquid motion on a gas-absorption coefficient, and was not intended for scale-up data. It is referred to here to show that the effect of fluid motion has been shown by them to be dominant and controlling for absorptions when agitation is used.

The process of gas desorption is currently being studied in our laboratories under conditions where fluid motion can be controlled, and for the purpose of evaluating the relations which must be known for scale-up. Some data are available for desorption of carbon dioxide from the surface of water to air in a 12-in. and an 18-in. diam. cylindrical tank (11, 13). The liquid is agitated by a flat-blade turbine mixing impeller. Baffles are used in the tanks for some runs, while in others, the baffles have been omitted. Figure 3, curve *A* illustrates the data and correlation for the case of desorption with baffles in the two sized tanks. Data for operation without baffles are also plotted in Figure 3, curves *B* and *C*.

When baffles are used the flow is characterized by the curve *CD* of Figure 1, and the liquid surface, in contact with carbon dioxide free air is substantially level, so that it is clear that inertia forces control the operation and the Froude group does not apply. Accordingly, the same flow motion can be achieved in both sized tanks, both as regards pattern and velocity. The dimensionless group by which a mass-transfer coefficient k can be correlated is kL/d where, d is the diffusivity. This is plotted logarithmically against the Reynolds number Ln/v. Data for both sized systems fall on a single line A, hence the relation of fluid motion and size are known for this reaction for a size ratio of 1.5 to 1. Also, the data show that dynamically similar fluid motion can be achieved at the two sizes and that this can be correlated with the desorption coefficient.

When baffles were removed from the two mixing tanks, vortexes were formed in each liquid, and it is apparent that

FLUID MOTION NOT SIMILAR
FOR SAME FLUID PROPERTIES
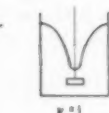
FLUID MOTION SIMILAR
WHEN FLUID PROPERTIES
ARE CORRECT

SCALE UP OF 2

$v = 1$

$v = 1$

$v = 1$

$v = 2.83$
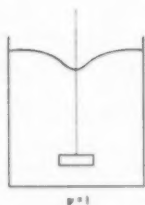
Fig. 2. Dimensionally similar systems, Reynolds and Froude forces effective.

○ 12 in. TANK
● 18 in. TANK

$\frac{hL}{d}$

$\frac{Lu}{v}$

Fig. 3. Relation between transfer coefficient and Reynolds number.

the flow can be characterized by a line like *BE* (Fig. 1). Also, Figure 2, left-hand side shows the ,type of vortex formed for equal Reynolds numbers in each tank using the same liquid at the same temperature. Under these conditions, both viscous and weight forces are effective, and therefore, the conditions of Equation (13) must be satisfied if similar flow is to be achieved. The curves *B* and *C* show data for the small and larger tank respectively. The data are not correlated for size by the plot, and this is to be expected when similitude is not present. Data are now being obtained for dynamically similar conditions by lowering the temperature of the solution (thus increasing its kinematic viscosity to 1.84 times that in the smaller tank), and taking into account the different diffusivity occasioned by the lower temperature. It follows that desorption or absorption data obtained with appreciable vortexing of liquid cannot be duplicated in a different sized dynamically similar system, since it is not possible to do so with the same liquid and temperature.

Unfortunately, most chemical reaction rates and equilibria are sensitive to temperature, and pilot operations are run at temperatures giving optimum yields. If the temperature in the model experiments must be the same as in the large scale unit, then vortexes in the liquid must be avoided. In fact, the fluid motion must, in these cases, be such as to be controlled by not more than one fluid property force. Under baffled conditions

in a mixing tank it is possible to use the same liquid at the same temperature in both the model and the prototype. These experiments show that the use of baffles in this desorption operation not only provide a better flow pattern for mixing (as evidenced by higher coefficients for equal power input) but also provides the necessary requirements for scale-up.

A number of references could be cited for data on the rate of solution of solid benzoic acid and solid salts in water, where the action took place in smooth wall cylindrical vessels without baffles using rotating impellers and deep vortexes were present. Such data correlate like those of lines *B* and *C* of Figure 3 and are useless for scale-up. Dynamically similar conditions on a larger scale cannot be achieved at the same temperature, and insufficient data were obtained at different liquid viscosities. Furthermore, complete geometric similarity of solid particle size was not achieved.

Some recent work of Mack and Marriner (*10*) on the rate of solution of solid benzoic acid in water were obtained in cylindrical vessels using rotating impellers and baffles. The conditions were correct for scale-up data, since no vortexes were present in the liquid surface and the flow characteristics were like curve *CD* of Figure 1. The data cover two sizes of tank and different solid "pill" size. When the data for the two size systems (pill ratio approximately constant) are recalculated to the mass-transfer group and plotted against
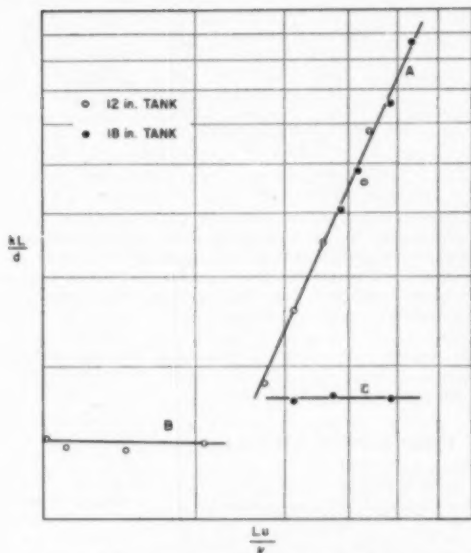
Reynolds number (Fig. 3) the data plot in a straight line similar to Curve *A*. Thus, these data were obtained under such conditions that scale-up can be made—at least over the size range studied, a scale ratio of 2 to 1.

These examples illustrate that data necessary for scale-up for this type operation can be correlated, provided that the requirements of similitude are taken into account.

Heat Transfer

The techniques of correlation of convection heat-transfer data with fluid mechanics relations and similitude are well known. Heat transfer in mixing tanks has also been correlated by the conventional techniques, and a few of the data of Chilton, Drew and Jebens (*4*) show that data taken under conditions of only slight vortexing can be correlated by the Nusselt group or "*J* factor" and the Reynolds number. For two sizes of equipment, scale 4 to 1, the data correlated as shown by curve *A* of Figure 3, where the *J* factor replaces the ordinate in the figure.

Other data from our laboratories (*6, 19, 20*) for heat transfer in mixing tanks from 1 to 4 ft. in diameter using vertical tubes for heat transfer and baffles (and the absence of vortexes) correlate in the same way as curve *A*, Figure 3, using appropriate heat-transfer parameters. Since the data were taken under flow conditions which allowed scale-up and similitude simultaneously, they are use-

IDEALIZED PACKING
IN A COLUMN

SIZE L = 1   SIZE L = 2
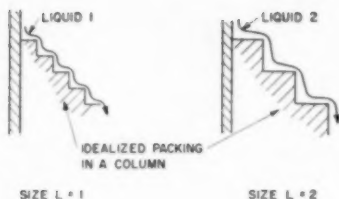
Fig. 4. Packed absorption
column.

IF BOTH REYNOLDS AND FROUDE FORCES ARE EFFECTIVE:
 TO ACHIEVE SIMILAR FLUID MOTION IN THE LIQUID THE KINEMATIC
 VISCOSITY OF LIQUID 2 MUST BE 2.83 TIMES THAT OF LIQUID I.
 IF THE SAME LIQUID VISCOSITY IS USED IN I AND 2 THE FLOW
 MOTIONS CANNOT BE SIMILAR, AND THE LIQUID FILM TRANSFER
 COEFFICIENTS CANNOT BE EQUAL.

ful for large size design. Successful scale-up of these data has been made to tanks 10 and 12 ft. in diameter (17).

Other Possible Applications

There are numerous data in the literature on the performance of packed towers and other equipment for gas-liquid and for liquid-liquid mass-transfer operations. Such operations involve fluid motion and are subject to the various kinematic forces. Few experiments have been made with the appreciation of the interplay of the various kinematic parameters in mind, and the fact that a change of scale and packing size may be of great significance in causing a change in fluid motion—all other things constant. Since at least two forces are usually operative in fluid motion in a packed column, it will be necessary to experiment in the pilot plant under "distorted" conditions of size or flow, so that the effective parameters can be evaluated individually. Figure 4 will serve to illustrate one possible situation in a packed absorption column where liquid is shown flowing down across steps of packing. It is clear that weight (or gravity) is important because of the wave shape of interface. Interfacial tension may be important especially if the curvature of the flow over the steps is sharp. Viscosity may be important if the velocity of flow is small and the viscosity high.

For the two sizes of packing there must be a difference in the fluid motion in each case depending on which two or more of the property forces are effective. This is evident also from the difference in appearance of the flow at the two sizes. Unless experimental data are obtained in the pilot plant to evaluate these force parameters in relation to scale, it will not be possible to make scale-up which allow even close approximation to dynamic similarity of motion, or to similar reaction rates.

Liquid-liquid extraction should be amenable to correlation for scale-up if the appropriate relations of Table 2 are observed. Drop size is a function of the Weber number, and is thus a function of fluid motion. Scale-up for drop and bubble size must be made with attention to the Weber number. The formation of drops of immiscible liquids due to high velocity streams such as are developed by mixing impellers in tanks, or by flow jets of liquid, is a function of interfacial tension and the Weber parameter must be taken into consideration. The relations in Table 2 require that interfacial kinematic tension must vary as some function of the scale, if dynamic similarity is to be obtained. Therefore, if the same liquids are used in two sized systems the

drop size cannot bear the same relation to system size (the chosen length basis, or the scale) in each case. This no doubt accounts for the fact that drops of liquid produced by mixing impellers are of different size when produced in different sized systems operating at the same Reynolds number. The rate of settling (or rise) of drops, once formed, is a function of viscous forces and Equation (12) gives the relation for translation from pilot plant to larger scale.

Some data are in the literature on distillation in wetted wall columns (2) which show that the H.E.T.P. is some function of the scale. However, the data were obtained as a by-product of experimentation for a different purpose, and the kinematic viscosity of the reflux liquid was not varied (as it might be by operation at different pressure and temperature), so that it is not possible to use relations of Table 2 to test for dynamic similarity and thus compare the performance under conditions of similitude.

Similitude relations are basic to the understanding of and application of flow in jets and the fluid surrounding the jet. Behavior of jets is dependent upon kinematic force parameters and data can be extended to fluids of the same kinematic viscosity (1, 7) when the velocities are such that fully developed turbulence is achieved.

A particularly interesting possibility for application of similitude principles is in the fluidizing operation. When a differential equation is written describing the flow and particle distribution in a fluidized stream, and operated on as described above for the case of viscous flow, it is possible to obtain a relation like Equation (18). The parameters determined therefrom set the similitude requirements. Experimental work on fluidizing have not, to the writer's knowledge, been designed with such complete relations in mind. Reynolds numbers have of course been used as criteria, but other less evident relations can be developed, and they should be investigated. It is of interest to note that similitude relations have been suc-

cessfully applied to the study of the transport and pick-up of silt in river flow. There are interesting analogies between such an operation and fluidizing.

Other interesting applications of the mechanics of similitude to fluid problems of direct interest to the chemical engineer can be found (5, 8).

Notation—Force Units

Mass units may be found by substituting Ma for F.

Mass, force, length, and time are related by $\dfrac{ML}{FT^2} = 1$

a = acceleration, L/T^2
A = area, L^2
D = diameter, L
d = diffusivity, L^2/T
e = kinematic bulk modulus of elasticity, L^2/T^2
F = force, $= Ma = ML/T^2$, or Mg
g = gravity constant, L/T^2
k = mass-transfer coefficient, L/T
K = a constant, dimensionless
K_e = dynamic bulk modulus of elasticity, F/L^2
L = length dimension, FT^2/M
L_r = scale ratio
M = mass, ft.$^2/L$, or F/g
N = revolutions per second
N_e = Cauchy number, dimensionless
N_{Fr} = Froude number, dimensionless
N_I = Newton inertia force group, dimensionless
N_{Re} = Reynolds number, dimensionless
N_{We} = Weber number, dimensionless
p = pressure intensity, F/L^2
P = power, FL/T
Q = flow, gal./min.
T = time, ML/F
u = velocity, L/T
γ = (gamma) specific weight, F/L^3
μ = (mu) dynamic viscosity, FT/L^2
ν = (nu) kinematic viscosity, L^2/T
ρ = (rho) density, ft.$^2/L^4$
σ = (sigma) interfacial or surface tension, F/L
ω = (omega) kinematic interfacial tension, L^3/T^2
a,b,c = linear dimensions
u,v,w = velocities in the x, y, z coordinate directions

Subscripts 1 and 2 refer to conditions 1 and 2.
Subscript r refers to the ratio of values at two conditions.

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Discussion

R. R. Hughes (Shell Development Co., Emeryville, Calif.): Although this paper accomplishes its main purpose of bringing out the need for dimensional analysis, there are two major points I must question. In the first place, no mention is made of thermodynamic similarity. Even though this may not be a criterion in the author's particular field of interest, some mention should be made of it, in view of the fact that thermodynamic and dynamic similarity cannot in general be met simultaneously. Secondly, I do not agree with Professor Rushton that it is impossible to scale-up while keeping the ratios between inertia forces and *three* or even more additional forces constant. For instance, scale-up can be made using a constant Reynolds number, a constant Froude number and a constant Weber number, if the surface tension and the viscosity of the fluid are both altered. Alteration of the surface tension may be more difficult than the viscosity alteration, but it should be noted that it is not impossible from a theoretical viewpoint. From a practical viewpoint the more use is made of special aids such as surface agents or viscosity producing agents, the more dubious are the results, because of extraneous effects, such as non-Newtonian behavior, time dependence of surface tension, etc.

J. H. Rushton: That's a valid observation. Correction has been made in the present form of the paper. Mention has been made that it is possible to approximate dynamically similar conditions when more than two force parameters are effective, that is, to distort the model so that you can evaluate independently the effect of viscosity, the effect of gravity, and the effect of interfacial tension. Model work on ships in towing basins is done in precisely that fashion. Now, obviously, the waves behind the ship must be supplied by energy put into the propellers of the ship and so, in ship motion, there is both a viscous force and a gravity force involved. If you use the same liquid in the same towing tank but use two different ship sizes, you cannot reproduce dynamic similarity. You should really use a liquid of higher viscosity and a larger tank. Or, since sea water is given for the large ship, then you should use a lower viscosity in the small model tank. However, by properly distorting the models so that the individual effect of the Reynolds number and the individual effect of the Froude number can be found, you can add the two effects and get the interrelation between the two. Analytically you can do so by simply equating the equations for velocity. I don't want to leave the impression that you cannot closely approximate dynamic similarity when three forces are in effect. Usually, one force predominates and the other forces may be neglected but it is up to you to determine whether they can be neglected.

R. R. Hughes: Modeling with three or more dynamic dimensionless groups can not only be done by distorted models but also, at least in theory, by actual models. For example, all three of the velocity ratios for pressure, weight, and viscosity forces in Table 2 can be set equal to each other, as follows:

$$u_r = \sqrt{L_r} = \frac{v_r}{L_r} = \sqrt{\frac{\omega_r}{L_r}}$$

The required change in viscosity and surface tension, is thus, respectively

$$v_r = L_r^{3/2}$$
$$\omega_r = L_r^2$$

If, practically speaking, these viscosity and surface tension factors can be attained, an exact model is possible.

C. R. Bartels (E. R. Squibb & Sons, New Brunswick, N. J.): Would the speaker comment on the possibility of reversing this technique in the case of a system affected by several forces and operated on several scales, and from the results of experiments determining which forces are effective?

J. H. Rushton: I'm sure you can determine the interplay between the forces by varying the scale. That is the feasible way, experimentally, I think, of determining the interplay between the different force properties.

John Happel (New York University, New York): I was interested in the discussion of Figure 2, in which it is stated that similar fluid motion is obtained with two different-sized tanks when both Reynolds and Froude numbers are maintained constant. When you showed in the moving picture the larger tank with propeller moving around that had the same Reynolds number as the smaller tank, but not the same Froude number, the indication was that there was only a slight vortex at the top of the larger tank. I could not help but be impressed by the fact that although the Reynolds number was the same in both cases, the propeller was rotating a lot more slowly in the case of the large tank. Doesn't dynamic similarity imply keeping constant both the inertia number and the Reynolds number? In that case, to get complete similarity, even assuming no vortex is formed, should you not have changed the viscosity so that the propeller was rotating at the same speed as it was in the smaller tank and also the Reynolds number was the same in the larger tank as in the smaller tank? Then you would have complete dimensional similarity but you would have had to change the viscosity to get it even in the presence of no vortex at all.

J. H. Rushton: You are correct in that the viscosity should be changed, as was shown. But speed must also be changed. The movie showed a 6-in. tank. In that tank there was a 2-in. impeller. The velocity at the tip of that impeller is πDN, where D is the diameter of the impeller and N is the rotational speed (revolutions per second). At a corresponding point in the larger tank, and if Reynolds number alone were controlling we should have one half the velocity and that velocity is πDN where D is now twice what it was before. Therefore, N must be one fourth what it was in the small tank to have the required velocity. However, Equation (12) shows what the velocity at corresponding points must be in order to achieve dynamic similarity at different size when viscosity is changed; and Equation (13) shows how viscosity must vary with size.

John Happel: It seems to me that if you want corresponding velocities the

propellers should be rotating at the same speed in the large tank as in the small tank. At a point twice as far out from the radius you have a velocity twice as great in the larger tank.

J. H. Rushton: We must be careful to distinguish between speed (revolutions per second) and velocity (feet per second). In scale-up, if it is a function of viscous forces, we should have velocities at corresponding points as predicted by Equation (12). In the motion picture illustration, when water was used in tanks whose size ratio was two, then corresponding velocities would be one half in the larger tank if viscous forces alone were controlling and complete similarity would exist.

J. C. Jubin (Atlantic Refining Co., Philadelphia, Pa.): In the paper there is an example given where two different liquids are mixed in the same time, where the scale-up ratio is 4: the tank size is 15 ft. in one case and 60 ft. in the other case. By your analysis, the hp. requirement comes out 16 times as much to get equivalent mixing. What were the relative tank turnovers, or in other words, how many times the volume of the tank is pumped by the mixer?

J. H. Rushton: The volume of the larger tank is 64 times that of the smaller one, and for geometrically similar propellers, the flow from the slower and larger propeller is 16 times that of the small one; so the turnover in the large tank is one fourth that in the small one. For blending operations, there may well be a simple relation between turnover and size.

E. A. Fike (Monsanto Chemical Company, Nitro, W. Va.): In the example with increased viscosity, a deeper swirl appeared while all other conditions remained the same. If reaction rate were determined by agitation, would you expect to get increased reaction rate in a case of that type merely by increasing the viscosity?

J. H. Rushton: No, I merely meant to show that you get a different flow motion for different viscosities. Now the flow motion you get might be better for your operation, although molecular diffusivity would no doubt be lowered as viscosity increased.

D. B. Keyes (Heyden Chemical Corp., New York): Would it be feasible to change the apparent density in order to increase reaction rates by the addition of an inert solid such as sand and keeping the liquid reactants agitated?

J. H. Rushton: This is an interesting speculation. We know that solids suspended in liquids do change the fluid motion of the liquid, and it is quite possible that a "pseudo-viscosity" could be achieved and that reaction rates could be altered by the addition of inert solids. The feasibility of the technique

would involve consideration of additions and separation of the inert solids, but such would not deter consideration of use of the idea for pilot plant work. Anything which will change fluid motion, and thus the convection currents, may well have an effect on the over-all rate of a chemical reaction.

J. J. Martin: Cannot all of this be stated rather simply by saying that two geometrically similar systems possess dynamic similarity of fluid motion when significant dimensionless force ratios such as the Reynolds, Froude, and Weber number but not including the Newton (or inertia) number are respectively the same for both systems?

J. H. Rushton: Certainly.

J. J. Martin: Isn't it true that if such numbers as the Froude, Weber, and Cauchy are not used in correlations of results on different chemical engineering processes, it is simply because in these applications gravitational, surface tension, and compressibility forces are found to have little effect on the operation?

J. H. Rushton: I doubt it. If this were so, why are these relations so often neglected? The purpose of this paper was to call attention to principles already well known but which have all too frequently been overlooked.

J. J. Martin: If, for example, surface tension is a proved variable in a certain operation, will it not appear in the results of a dimensional analysis of that operation and specifically, can it not be made to appear in the Weber number if size, velocity, and density are also significant variables?

J. H. Rushton: Yes, of course.

J. J. Martin: Isn't it true that "a coefficient of blending" just as a coefficient of heat transfer would be involved with tank diameter and diffusivity in a dimensionless group which would depend upon Reynolds number, ratio of impeller diameter to tank diameter, and any other significant, dimensionless ratios rather than upon the Newton or inertia number?

J. H. Rushton: Yes, Figure 3 and (17) show that. The inertia number would also be characteristic.

J. J. Martin: What justification is there for scaling-up a blending operation on the basis of equal Newton (inertia) numbers and equal time scales?

J. H. Rushton: The illustration was taken from commercial operating data and the results check the postulated theory.

J. J. Martin: Isn't it true that in the majority of agitation systems employed in industry means are taken to prevent vortexing and therefore surface waves are negligible, meaning that dynamic similarity in geometrically similar sys-

tems depends upon equality of Reynolds numbers alone?

J. H. Rushton: Most mixing operations are performed with equipment arranged to prevent vortexing, and unless this is done it is not convenient, if indeed possible, to relate the results to small-scale laboratory work. Therefore, I urge that small-scale mixing experimentation be done under these conditions and then dynamic similarity will be achieved at equal Reynolds numbers.

Written Discussion

J. J. Martin (University of Michigan, Ann Arbor, Mich.): It seems advantageous to express some principles of fluid mechanics in a manner slightly different from Professor Rushton's. Chemical engineers are not completely oblivious to the conditions of geometric and dynamic similarity (see "Unit Operations")[*] and are rather familiar with Reynolds number, the ratio of inertia to viscous force. Perhaps they are not so familiar with other dimensionless force ratios, but that is because these ratios are of lesser importance in most chemical engineering applications and not because they have been ignored or overlooked.

A look at the problem of determining the force to push geometrically similar objects through fluids with constant velocity will demonstrate the application of these dimensionless force ratios. Granting negligible surface or compressibility effects for the moment, this force is given by the well-known drag equation, which can be derived by dimensional analysis or from an application of Newton's momentum principle,

$$F = \rho A u^2 \phi(L u \rho/\mu) \qquad (1)$$

where ρ is the density of the fluid, μ is its viscosity, L is a characteristic length of the object, A is the cross-sectional area of the object, and u is the velocity of the object relative to the fluid. The area A may be expressed as the length squared, L^2, and the equation may be written in completely dimensionless form by dividing through by $\rho L^2 u^2$,

$$(F/\rho L^2 u^2) = \phi(L u \rho/\mu) \qquad (2)$$

Although the dimensionless group on the left may be called the inertia group, it appears more logical to call it the Newton number (Newton developed Equation (2) with right-hand side equal to a constant) and to say that it is the ratio of the applied force or pressure to the inertia force just as Reynolds number is the ratio of inertia to viscous force. Now if with different size objects

[*] "Unit Operations"—G. G. Brown and Associates, John Wiley & Sons, New York (1950).

the fluid motions are dynamically similar, the Reynolds numbers for the two systems are the same, from which it follows the Newton numbers are the same. However, equal Newton numbers do not imply dynamic similarity, for the Newton number is often constant for a wide range of Reynolds numbers for those cases where viscous forces are small.

Suppose now our attention is turned from measurement of applied forces to a study of the heat transfer between the same object and the fluid. Instead of utilizing the drag equation, one employs a typical heat-transfer equation, again obtained by dimensional analysis,

$$hL/k = \phi(Lu\rho/\mu, c\mu/k)$$

or

$$(hL/k, c\mu/k) = \phi(Lu\rho/\mu) \tag{3}$$

where h is the heat-transfer coefficient, k is thermal conductivity of the fluid, and c is its heat capacity. When dynamic similarity exists in two different systems, the Reynolds numbers are the same and it follows that the expression $(hL/k, c\mu/k)$ which involves the Nusselt and Prandtl numbers is the same for the two systems. Furthermore, the expression $(hL/k, c\mu/k)$ will not be constant when viscous forces are small even though the Newton number will be constant, so the expression depends on the Reynolds number and not on the Newton number.

Let us now return our attention to the applied forces in a situation where as the object is moved through the field, significant waves are formed at the surface of the fluid. This simply means that gravitational acceleration g will be an important force to be considered and the familiar drag equation becomes by dimensional analysis,

$$(F/\rho L^2 u^2) = \phi(Lu\rho/\mu, u^2/Lg) \tag{4}$$

which says that the Newton number is a function of the Reynolds number and the Froude number. If dynamic similarity exists in two different systems, the Reynolds and the Froude numbers are respectively the same in both systems, from which it automatically follows that the Newton numbers are the same in the two systems.

If the heat-transfer problem is reconsidered for this case where wave effects are significant, it means that the expression involving the Nusselt and Prandtl numbers is some function of the Reynolds and Froude numbers or

$$(hL/k, c\mu/k) = \phi(Lu\rho/\mu, u^2/Lg) \tag{5}$$

And again if dynamic similarity exists in two different systems, the Reynolds and Froude numbers are respectively the same in the two systems and the expression involving the Nusselt and Prandtl numbers must be the same.

Obviously, the treatment can be extended to include any other effects of importance in a given operation, but it is to be noted that dynamic similarity exists at equal values of Reynolds, Froude, etc., numbers, but not necessarily at equal values of the Newton number.

The condition of dynamic similarity is worthy of further consideration. If we examine two geometrically similar systems in which both viscous and gravitational forces are significant, we may write

(Reynolds No.)

$$L_1 u_1 \rho_1 / \mu_1 = L_2 u_2 \rho_2 / \mu_2$$

or

$$u_1/u_2 = L_2 \rho_2 \mu_1 / L_1 \rho_1 \mu_2 \tag{6}$$

(Froude No.)

$$u_1^2/L_1 g = u_2^2/L_2 g$$

or

$$u_1/u_2 = (L_1/L_2)^{\frac{1}{2}} \tag{7}$$

from which

$$(\mu/\rho)_1/(\mu/\rho)_2 = (L_1/L_2)^{3/2} \tag{8}$$

The last expression tells us that if dynamic similarity is to exist in two different size systems, either we must make the linear dimensions conform to the ratio of μ/ρ for the two fluids selected, or we must select two fluids with the correct ratio of the μ/ρ's to conform to the linear dimension ratio. Now suppose surface tension γ is another significant force; in order that dynamic similarity exist, the Reynolds, Froude, and Weber numbers must all be respectively the same in the two systems, or in addition to Equations (6) and (7), we have an additional relation

(Weber No.)

$$L_1 u_1^2 \rho_1 / \gamma_1 = L_2 u_2^2 \rho_2 / \gamma_2$$

or

$$u_1/u_2 = (L_2 \rho_2 \gamma_1 / L_1 \rho_1 \gamma_2)^{\frac{1}{2}} \tag{9}$$

Combining Equations (7) and (9),

$$(\gamma/\rho)_1/(\gamma/\rho)_2 = (L_1/L_2)^2 \tag{10}$$

Now, although it might be difficult to find a fluid whose properties satisfy simultaneously both Equations (8) and (10), still one must not say that it is impossible. Therefore, dynamic similarity can be obtained when three force properties of the fluid such as gravity, viscosity, and surface tension, are important.

When considering agitation problems, one must be careful to distinguish between the flow conditions which exist in the neighborhood of the impeller and those which exist throughout the tank. The fact that the impeller is operating in a range where the Newton number is independent of the Reynolds number does not mean that viscosity is of no importance to the operation as a whole. A small impeller rotating at high velocity in a large tank of viscous liquid may well find the bulk of its resisting force to be inertial in nature, but viscosity may be influencing the transport of material at points well removed from the impeller.

The problem of blending two liquids in the same length of time in systems differing in size by a factor of 4 is most interesting. According to Professor Rushton, the power requirement of the larger system is 16 times the power requirement of the smaller. Since volume varies as the length cubed, the larger system contains 4^3 or 64 times as much liquid as the smaller. This means that the power required per unit volume of liquid is 16/64 or one fourth as great for the larger tank as for the smaller tank, a result which is worthy of further attention. Professor Rushton arrives at the figure by saying that the scale-up is based on equal Newton numbers and equal time scales. Another mode of attack may prove equally enlightening: Let us first assume the two systems are operated in such a way that the fluid motion is dynamically similar, and that the fluids being blended are of practically the same density and viscosity so that one value of these properties may be used. Neglecting surface effects, the Reynolds numbers are equated to give

$$L_1 u_1 \rho_1 / \mu_1 = L_2 u_2 \rho_2 / \mu_2$$

or

$$u_2 = u_1(L_1/L_2) = u_1/4$$

for blending the same fluids in systems where $L_2 = 4L_1$.

Since the velocities in the larger tank are only one fourth as great as those in the smaller tank and since the distances to be traveled are four times as great, it would appear at first that it would take 16 times as long for elements of the fluids to move through corresponding paths in the larger tank. In order to accomplish motion along this path in the same length of time, it would appear that the velocity should be increased 16 times assuming that viscosity effects are negligible. This will mean a larger Reynolds number must be employed in the larger tank and more power must be consumed. Since power consumption is proportional to $u^3 L^2$ and power per unit volume of fluid agitated

is u^3L^2/L^3 or u^3/L, it follows that when the two systems are operating at the same Reynolds numbers the power per unit volumes are as follows:

$$(P/L^3)_1 = u_1^3/L_1$$

and

$$(P/L^3)_2 = u_2^3/L_2$$
$$= (u_1^3/64)/(4L_1)$$
$$= (P/L^3)_1/256$$

This would mean that at equal Reynolds numbers the larger tank would require only 1/256 as much power per unit volume.

If the velocity in the larger tank is increased 16 times

$$(P/L^3)_2 = (16^3 u_1^3/64)/(4L_1)$$
$$= 16(P/L^3)_1$$

In other words if the assumption is made that at equal Reynolds numbers it would take 16 times as long for the fluids to move through corresponding paths in the larger tank, then by increasing the velocity in the larger tank 16 times, the job would be finished in the same length of time and would require 16 times as much energy applied to each unit volume of fluid. However, the transfer of material by turbulent motion is not proportional to the velocity alone in those situations where the scale of turbulence† is small. With small impellers the scale of turbulence is not great and according to the laws of eddy

† Scale of turbulence can be thought of as the average distance traveled by a given mass of fluid before it breaks up and loses its identity.

diffusion the transfer of material by small scale turbulent motion is proportional to the product of the intensity (velocity) and the scale (where the scale is some fraction of the size of the euipment). This means that in the larger tank when operating at the same Reynolds number as the smaller tank the material is transferred at a rate of $(u_1/4)(L_2/L_1)$ or $(u_1/4)(4/1)$, which is just as fast as in the smaller tank instead of one fourth. Therefore, to accomplish the transfer through corresponding distances in the same time in the large tank would require that the velocity need be increased only four times to account for the increased distance alone. This gives the power per unit volume in the large tank as

$$(P/L^3)_2 = (4^3 u_1^3/64)/(4L_1)$$
$$= (P/L^3)_1/4$$

or only one fourth as much power per unit volume is required in the large tank as in the smaller tank. If larger impellers were used to create larger scale turbulence, the laws of eddy diffusion show that the transfer of material by such large-scale turbulence is proportional to the velocity and independent of the scale, and therefore, the larger tank might require 16 times as much power per unit volume. In the problem cited where the impeller diameter is 1/30 the tank diameter the scale of turbulence is small and the use of ¼ as much power per unit volume in the large tank as in the small tank seems justified; though, even here there is some question whether the

blending has taken place to the same degree of "fineness" in both tanks. Since the scale of turbulence is greater in the larger tank, the "clumps" of liquid which have been mixed are larger, and molecular diffusivity is called upon to do more of the job to produce the final homogeneous state.

The important point is that one cannot arbitrarily scale-up a blending operation by simply equating the Newton numbers and saying the time scales are the same. Blending is a mechanism that does not depend on Newton number but does depend on Reynolds number, size of tank, relative impeller and tank dimensions, diffusivity and other fluid properties, just as the heat transfer is independent of Newton number but dependent on L, k, μ, ρ, and other fluid properties. In fact the bulk of chemical engineering operations such as blending, promoting chemical reaction, extracting, absorption, etc., do not depend upon Newton numbers but depend upon Reynolds number or numbers needed to describe dynamic similarity along with other numbers involving the fluid and system properties. The other numbers can be introduced by proper dimensional analysis to give equations similar to (4) and (5), but it is not probable that the Newton number will ever appear as an independent variable as it depends on the other numbers which determine dynamic similarity.

(Presented at White Sulphur Springs (W. Va.) Meeting.

(The End)

DRYING OF GASES

Adsorption Wave in Desiccant Beds

STANLEY H. JURY* and WILLIAM LICHT, JR.

University of Cincinnati, Cincinnati, Ohio

T HE passage of a fluid stream through a stationary bed of granular solids may involve the transfer of ma-

* Present address: University of Tennessee, Knoxville, Tenn.

terial or heat (14). For example the passage of hot gases through a checkerwork of cold brick involves the transfer of heat from the hot fluid to the cold solid. Likewise the passage of humid

gas through a stationary bed composed of granules of a solid desiccant involves the transfer of material (water vapor) from the gas to the solid. In certain cases such transfer of material is due to

adsorption (11). The transient conditions which prevail during adsorption in a desiccant bed give rise to an "adsorption wave" (concentration gradient in the fluid stream) which originates at the entrance and gradually moves toward the opposite end of the bed. It is the theory of the motion of this wave and its applications that have attracted much attention during recent years (4, 11, 14, 15, 17, 19, 20-22).

Development of the theory requires the solution of the partial differential equation describing the behavior of the bed, and the solution of this equation in turn falls into a number of separate cases depending upon the kinetic mechanism of the adsorption process. Anzelius (1) and Nusselt (12) have given the solution for the case where mass transfer in the gas stream is the rate-controlling factor and Schumann (13) and Furnas (5) have presented this solution in the form of a standard chart which is convenient to use.

The first purpose of this paper is to present the solutions for two other cases, and to show how by utilizing a dimensionless form all three cases may be reduced to a single generalized theory. This treatment has many advantages, particularly in problems of the design of drying units and in studies of the kinetics of an adsorption process. The second purpose is to present the results of an investigation of the kinetic mechanism of the reaction between humid air and the granular desiccant, anhydrous calcium sulfate. Plots of the experimentally determined adsorption waves are presented for various sets of operating conditions as controlled by the variables: gas velocity, granule size, and length of bed. An analysis of the plots is presented wherein the generalized theory as well as other available means are employed.

Generalized Theory

The present theory of the adsorption wave (4, 11, 22) is based on a material balance over a differential element of the bed. The amount of water passed into the element is equal to that adsorbed by the element plus that which is exhausted from the element. The humidity and velocity of flow of the gas stream are assumed to be uniform throughout the cross-section of the bed at any instant. Changes in gas density and volume due to the removal of vapor by adsorption, and pressure drop over the bed are neglected. The process is assumed to be isothermal. Whenever the adsorption isotherm is involved it is assumed that it is a straight line. Both the initial humidity and the rate of flow of the gas stream are assumed to be constant. As a consequence of all these assumptions the material balance applies to a limited case. Such limited consideration is necessary in order to avoid insuperable mathematical difficulties which would arise later.

Klotz (11) has given a derivation of the material balance for the ideal case. It may be written as

$$\frac{\partial H}{\partial Z} + \frac{\rho_b}{a V \rho_0} \frac{\partial W}{\partial t} = 0 \qquad (1)$$

where

H = absolute humidity of gas stream at any point (based on bone-dry gas), lb./lb. of gas

t = exposure time, hrs. = $(t' - Z/v)$ where t' = total time that feed is fed to bed

V = average lineal gas velocity through the interstices between the granules in the bed, ft./hr.

W = moisture content of adsorbent (based on bone-dry adsorbent), lb./lb. adsorbent

Z = distance into the bed measured from entrance in the direction of flow, ft.

a = fraction external voids in bed, cu.ft./cu.ft. of bed

ρ_b = bulk density of dry adsorbent bed, lb./cu.ft.

ρ_0 = density of gas stream at the prevailing temperature and pressure, lb./cu.ft. of gas

Wicke (20, 21) has discussed the equivalent of Equation (1) in connection with the problem of internal diffusion without having solved the equation for this particular case.

The desired solution of Equation (1) will be a functional relationship $H = f(Z,t)$ subject to the necessary boundary conditions. In order to obtain this solution under the circumstances described one must replace W in terms of H, Z, and t. This requires knowledge of, or at least an assumption of, the mechanism by which the adsorption occurs.

In some instances diffusion of moisture from the surface into the interior of the granules may control the over-all rate of the drying process. Assuming this to be the case, it may be deduced from the work of Wicke (20, 21) that

$$\frac{\partial W(Z,t)}{\partial t} =$$

$$\frac{6Bk^2}{\pi^2} \sum_{v=1}^{\infty} \int_0^t e^{-v^2 k^2 (t-s)} \frac{\partial H(Z,S)}{\partial S} dS \qquad (2)$$

where:

$W = BH$ is the equation of the linear adsorption isotherm

v = summation variable

k^2 = a constant depending upon properties of the granule as described below, and having units of (hours^{-1}.)

S = variable of integration

Equation (2) may be simplified by assuming that for longer times the first term of the summation represents approximately the value of the series. Substitution of the result in Equation (1) gives an equation which upon differentiation becomes:

$$\frac{\partial^2 H}{\partial T \partial X} + \frac{\partial H}{\partial X} + \frac{\partial H}{\partial T} = 0 \qquad (3)$$

Equation (3) has been placed in a generalized form by using the dimensionless variables X and T, so defined that

$X = k^2 D Z$ is proportional to Z, the bed length, (4)

$T = k^2 t$ is proportional to t, the elapsed time, (5)

and

$$D = \frac{B\rho_b}{a V \rho_0}$$

The boundary conditions to be met are:

$H = H_e$ at $X = 0$ for all values of T

$W = 0$ at $T = 0$ for all values of X

Equation (3) may be solved by using various standard procedures (17).

The method of Laplace transform (11a) applied to Equation (3) under the specified boundary conditions leads to a solution in the form:

$$\frac{H}{H_e} = 1 - e^{-T} \int_0^X e^{-S} I_0(2\sqrt{TS}) \, dS \qquad (6)$$

where I_0 denotes the Bessel function of imaginary argument, and S is the variable of integration. The integral is one of historical interest and is recognized as Weber's first integral (18). It may be evaluated exactly in terms of Bessel functions and generalized hypergeometric functions. These are tedious to evaluate for the large values of X and T which are usually of interest. When $r > 1$, however, one may employ the asymptotic expansion (23)

$$I_0(r) = \frac{e^r}{\sqrt{2\pi r}} \qquad (7)$$

This substitution reduces Equation (6) to

$$\frac{H}{H_e} = \frac{1}{\sqrt{\pi}} \int_X^\infty \left(\frac{S}{T}\right)^{\frac{1}{4}} e^{-(S^{\frac{1}{2}} - T^{\frac{1}{2}})^2} \frac{dS}{2 S^{\frac{1}{2}}} \qquad (8)$$

The factor $(S/T)^{0.25}$ may be considered to be unity so that the remaining integral reduces to the error integral and

$$\frac{H}{H_e} = \frac{1}{2} [1 + \phi(Y)] \qquad (9)$$

where

$$\phi(Y) = \frac{2}{\sqrt{\pi}} \int_0^Y e^{-r^2} dr$$

and

$$\phi(-Y) = -\phi(Y)$$

and

$$Y = T^{\frac{1}{2}} - X^{\frac{1}{2}}$$

only the positive roots being used.

The error integral $\phi(Y)$, is easily evaluated from the readily available tables of this function. Arithmetic-probability paper may also be used.

Fig. 1a. Equilibrium moisture adsorption isotherm for 42-48 Tyler mesh drierite at 65-90° F.

The fact that Equation (9) may be considered to be a generalized solution may be shown by considering three different cases. In each case an appropriate definition of X and T leads to the same differential Equation (3) and to the same general Equation (9). It will be noted that $\bar{Z}$ and T are always dimensionless quantities and contain k^2. The first case which is the one above is one of activated diffusion through a lattice structure which has been described by Tiselius (16) and Hey (6-8). For this case

$$k^2 = \left(\frac{\pi}{R}\right)^2 D_I \qquad (10)$$

where

R = granule radius, ft.
D_I = internal diffusion coefficient, sq. ft./hr.

The value of k^2 is to be used in conjunction with the definitions of X and T in Equations (4) and (5).

The second case is one of diffusion through relatively large pores of a porous granule such as carbon. This case has been considered by Wicke (20, 21) for carbon and carbon dioxide under rather special circumstances. It may be shown that Equation (9) is also the solution to this case provided X and T are defined as

$$X = \left(\frac{\pi}{R}\right)^2 D_I \frac{\rho_D}{a\sqrt{\rho_P}} \left(1 - \frac{\rho_P}{\rho_S}\right) \bar{Z} \qquad (11)$$

$$T = \left(\frac{\pi}{R}\right)^2 D_I \frac{\rho_D}{B\rho_P} \left(1 - \frac{\rho_P}{\rho_S}\right) t \qquad (12)$$

where

ρ_P = apparent density of dry porous granules, lbs./cu.ft.

ρ_S = true density of solid adsorbent, lbs./cu.ft.

Evaluation of the diffusion coefficient D_I will be discussed below.

The third case to which the generalized theory applies is that in which mass transfer to the surface of the granule is the rate-controlling factor. It has been shown for this case that (1, 5, 9, 12, 13, 18)

$$\frac{H}{H_o} = 1 - e^{-x} \int_o^{xT} e^{-S} I_o(2\sqrt{ST})dS \qquad (13)$$

The Schumann-Furnas chart as presented by Hougen and Marshall (9) is a graphical representation of this equation as well as for all cases previously considered. The definitions of X and T for this case are

$$X = \frac{K_g a}{a\sqrt{\rho_D}} \bar{Z} \qquad (14)$$

$$T = \frac{K_g a B}{a\rho_D} t \qquad (15)$$

where

K_g = mass-transfer coefficient, lbs./ (hr.)(sq.ft.)(unit abs. humidity)

a = superficial surface of granules (ignoring pore structure) per unit volume of bed, sq.ft./cu.ft.

It has been found that in general

$$K_g a \propto V^{.8} R^{-1.0} \qquad (16)$$

The concept of the generalized theory Equations (6) and (9) may be extended to other cases as well. Activated shell penetration and second-order reversible chemical reactions when the rate constants are equal are two such additional examples. It can be shown too that the generalized theory for what amounts to first-order processes is actually a special case of an even more general second-order theory developed by Thomas (15). Certain of the latter extensions of theory will be presented elsewhere.

The Adsorption Isotherm. As a matter of implementing the research reported in the next section of this paper it was necessary to determine the adsorption isotherm at room temperature

TABLE 1.—EQUILIBRIUM MOISTURE CONTENT OF DRIERITE SAMPLES (at 65 — 90° F.)

Per Cent Relative Humidity	Moisture Adsorption (per cent by weight) (absolute dry basis) = $W \cdot 100$			
	2 — 2½ mesh		42 — 48	
$R_h = p/p_o \cdot 100$	In	Out	In	Out
0.0313	0.439	....	0.449	....
0.408	0.735	....	0.802	....
1.	....	6.12	....	5.81
2.	....	6.16	....	5.89
3.63	6.2	....	5.93	....
5.	....	6.3	....	6.02
10.	6.42	....	6.13	....
25.	....	6.53	....	6.28
35.	6 66	....	6.41	....
40.	....	7.08	....	6.76
50.	7.87	7.74	7.05	7.42
65.	8.1	....	7.68	....

Fig. 1. Effect of granular size on adsorption wave in beds of 3 in. length; air flow rate 9.4 cu.ft./hr.

for the system soluble anhydrite and water vapor. The soluble anhydrite used in all the experimental work was the commercial desiccant Drierite.

In the determination of the equilibrium adsorption isotherm an attempt was made to approach equilibrium from both directions, i.e., both adsorption and desorption, or "in" and "out" curves were obtained for new samples of Drierite. Some results are briefly summarized in Table 1 and Figure 1a. The adsorption capacities indicated in this table are computed on an absolute dry basis which means the dry weight of the sample was taken after 24-hr. ignition at 800° F. (as contrasted with the regenerated dry weight). It was found that a regenerated sample (2 hrs. at 400° F.) may still contain up to 1 per cent water on the absolute dry basis.

In general the adsorption isotherms indicate that soluble anhydrite behaves very much the same as ordinary crystal hydrates, i.e., isotherm contains nearly vertical followed by flat portions. The knee suggests some zeolitic activity (6, 7, 8, 10) between .408 and 10 per cent relative humidity. The small differences between the adsorption and desorption isotherms may be attributed to departure from equilibrium rather than hysteresis effects. The details of this work will be reported elsewhere.

The Adsorption Wave. Experimental determinations of the adsorption wave were made by determining the humidity of the effluent air stream from a fixed bed as a function of time. This was done by employing an automatic frost point hygrometer (9a) especially designed and constructed for this work. Data obtained with it are plotted in the form of H vs. t curves such as those shown in Figures 1 to 6. In order to test the theoretical equations developed above and to determine the rate-controlling mechanism of the adsorption process it was necessary to investigate the effect of the bed length, air flow rate, and desiccant granule size upon the $H - t$ curve.

All the beds were tested with a standard air of the same initial humidity. This was equivalent to an average frost point of +10.3° F. at one atmosphere or about 8.1% relative humidity at 72° F. (abs. humidity, H_o, equal to 1308×10^{-6}). The humidity of the feed air was kept low in order to avoid undesirable temperature effects. It was also within the region of linearity with regard to the adsorption isotherm.

The standard air supply was produced by passing compressed air at 29 lbs./sq.in. gage through a copper coil enclosed in a heavily insulated chest containing cracked ice and water. The coil was provided with a condensation trap from the top of which the standard air supply was drawn off and then reduced to prevailing atmospheric pressure. The humidity of the air so treated was found experimentally to correspond to that of air saturated at 33° and 29 lbs./sq.in. gage.

The standard air was passed through a rotameter and then into the bed which was equipped with a by-pass line and mercury
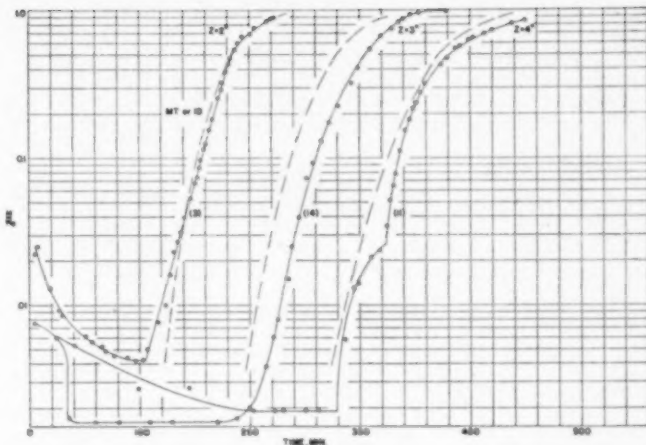
Fig. 2. Effect of bed length on adsorption wave in beds containing 20-24 mesh granules; air flow rate 9.4 cu.ft./hr.

manometer. The bed exhausted through a copper line which led into the frost point hygrometer. The hygrometer was protected against dust by small steel wool filters fitted in the bushings of the bed container. The humidity of the effluent air was thus determined continuously during a run by measurement of its frost point; as the bed gradually exhausted the frost point rose. These frost-point readings were converted into values of absolute humidity, H, by using the published vapor pressure data for ice (3).

The bed containers consisted of 1.03 in. I.D. brass nipples equipped with couplings and ½-in. to 1-in. bushings fitted with brass flare fittings. The containers were also provided with fine mesh screen stops. These were made from ½-in. sections of a running thread nipple by soldering the

screen to one face of the section. The stops were inserted into the couplings by placing screen first and turning with a spanner wrench until the screen had passed sufficiently far into the coupling so as to butt snugly against the desiccant material and the end of the nipple.

The bed container with a screen and bushing already in place in one end was charged with a sample of soluble anhydrite taken directly from the furnace in which it had been regenerated. During filling the container was tapped until no more settling took place. The level of the bed was even with the exposed end of the nipple. The second screen and nipple were put in place and the flare fittings capped. All joints were painted with beeswax and the container sealed until it was used for a test run. No desiccant was used directly as sup-

Fig. 3. Effect of air flow rate on adsorption wave in beds of 3 in. length; granule size 20-24 mesh.

Fig. 4. Effect of air flow rate on adsorption wave in beds of 2 in. length; granule size 20-24 mesh.

the steel wool filters in the system tend to hold up moisture which is removed during the initial portion of the run.

In order to determine the effect of the filters, the 9-in. bed container was placed in the test assembly without a desiccant charge. Instead of the dehumidifier a new tank of nitrogen was connected to the system and the gas flow rate to the test assembly was adjusted to 9.4 cu.ft./hr. The frost point of the gas exhausted from the assembly was determined in the usual manner. Results are tabulated in Table 2. This experiment confirms the fact that the apparatus holds up a certain amount of moisture. In subsequent work these filters were removed. No difficulty due to dust was encountered and the initial downward portions of the curves disappeared. The humidity dropped immediately to its minimum value and remained there until the bed "broke" and the rising or exhausting portion of the run began.

Analysis of Results

The analysis of results was carried out in two ways: (a) following the conventional empirical procedure outlined by Klotz (11) and, (b) a direct test of the theoretical equations just developed.

In accord with the empirical method of analysis outlined by Klotz (11) an arbitrary "break" concentration may be selected and designated, say $H_b/H_o = .01$. The "break" time, t_b, corresponding to the break concentration may then be read from Figure 1 for the four granule sizes and plotted as in Figure 7. In this and other plots to follow, each datum point is identified by a bracketed number which is the run number. Now, in accord with the postulates of the analysis, the curve should rise to longer break times as the particle size decreases provided mass transfer is a contributing factor (Equation (17) later will indicate unfortunately that this is also true for internal diffusion). For the smaller particle sizes according to Klotz the curve should approach some maximum value provided some sort of surface reaction becomes the controlling factor. Even though the curve in Figure 7 indicates no maximum it can be shown from equilibrium calculations that the 3-in.

plied; in general it was heated for 2 hrs. (no more) at 400° F. in order to insure that it would be active.

Four different granule sizes were investigated, i.e., 2-2½ mesh, 4-5 mesh, 10-12 mesh, and 20-24 mesh (Tyler standard screen mesh). The maximum air flow rate was 9.4 cu.ft./hr. because an independent study in 1-in. glass tubes demonstrated that 20-24-mesh beds show signs of agitation at flow rates exceeding this by about 15 per cent.

Typical results of the investigation are summarized in Figures 1-6. Numbers placed at the lower portion of the curves are run numbers. The dash curves are those taken from the Schumann-Furnas chart in accord with the theory and are the subject of subsequent analysis.

The 20-24-mesh granules in 3-in. beds were investigated in detail in order to determine the reproducibility of data. Runs 8, 13, and 14 are triplicates at a flow rate of 9.4 cu.ft./hr. They are compared in Figure 5. Likewise runs 10 and 15 are compared in Figure 5 to show the reproducibility of data at a flow rate of 7 cu.ft./hr. A 9-inch bed was run to confirm certain theoretical predictions to be discussed later. The adsorption wave for this run is shown in Figure 6.

In general all the adsorption waves presented in Figures 1-6 show a downward trend during the early stages of a given run. Amero (1a) reported similarly for Fluorite and attributed it to an "induction period." The cause may lie in the manner of preparation of the bed and/or in this case the fact that

Fig. 5. Reproducibility of adsorption wave in beds of 3 in. length containing 20-24 mesh granules.

TABLE 2.—FROST POINT OF NITROGEN EXHAUST FROM EMPTY ASSEMBLY

Time, min.	Frost Point, ° F.	Pressure in Nitrogen Bottle lb./sq.in.ga.
0	.....	1750
21	—32.5	....
36	—33.5	1550
42	—34	1540
72	—50	1390
98	—50	1260
121	—51.5	1150
Nitrogen by-passed around bed container and filters:		
150	—51.5	1050

bed in question can not last more than a maximum of 367 min. even for an infinitely fine-grained bed.

Figure 8 has been constructed for the arbitrary break concentration $H_b/H_o = 0.01$ based on Figure 2, 3 and 4; consequently a particular flow rate is associated with each datum point. The criterion according to Klotz is that if those points associated with one flow rate fall on a line distinctly different from those for other flow rates, then mass transfer is a contributing factor. This is based on the observation by Klotz (11) that the solution to the partial differential equation for mass-transfer controlling shows that t_b is a function of V as well as Z/V. For other cases which he examined he observed that t_b was a function of Z/V but not of V. In the light of the foregoing, Figure 8 suggests that mass transfer is not controlling in the present case.

Figure 9 is presented as a matter of passing interest. It is also a conventional plot. The critical length is defined as the shortest bed that will produce an effluent concentration less than or equal to the break value. This bed has no life because although the bed starts with an effluent at or below the break value an instant after operation the effluent concentration rises above this value. The "life thickness" curve plotted in Figure 9 has been constructed based on data taken from Figure 2. Its only purpose is to illustrate the fact that the critical bed depth for soluble anhydrite under these test conditions is very small. For

Fig. 6. Adsorption wave in bed of 9 in. length containing 20-24 mesh granules; air flow rate 9.4 cu.ft./hr.

adsorbents used in small portable units such as activated carbon in gas masks the critical bed depth becomes an important factor.

The empirical analysis leaves much to be desired. It is known now from Equation (9) that for a fixed value of H/H_o the value of Y is also a constant. Hence for internal-diffusion controlling

$$t_b^{1/2} = \left[\frac{B\rho_B}{a\rho_G}\right]^{1/2}\left[\frac{Z}{V}\right]^{1/2} - \frac{RY}{\pi D_I^{1/2}}$$
(17)

or

$$\frac{t_b^{1/2}}{R} = \left[\frac{B\rho_B}{a\rho_G}\right]^{1/2}\left[\frac{Z}{R^2V}\right]^{1/2} - \frac{Y}{\pi D_I^{1/2}}$$
(18)

and for mass-transfer controlling

$$t_b^{1/2} = \frac{1}{B^{1/2}}\left[\left(\frac{Z}{V}\right)^{1/2} - \left(\frac{a\rho_G}{Kga}\right)^{1/2}Y\right]$$
(19)

or if

$$Kga = K^1\frac{V^{1/2}}{R^{3/2}} \; ; \; K^1 = \text{constant}$$
(16)

then Equation (18) becomes

$$t_b^{1/2} = \frac{1}{B^{1/2}}\left[\left(\frac{Z}{V}\right)^{1/2} - \left(\frac{a\rho_G}{K'}\right)^{1/2}Y\frac{R^{3/4}}{V'^{1/4}}\right]$$
(20)

and

$$\left(t_b\frac{V}{Z}\right)^{1/2} = \frac{1}{B^{1/2}}\left[1 - \left(\frac{a\rho_G}{K'}\right)^{1/2}Y\frac{R^{3/4}V^{1/4}}{Z^{1/2}}\right]$$
(21)

Equation (18) suggests plotting for rate-controlled reaction

$$\frac{t_b^{1/2}}{R} \; vs. \; \left(\frac{Z}{R^2V}\right)^{1/2}$$

and Equation (21) suggests plotting

$$\left(t_b\frac{V}{Z}\right)^{1/2} \; vs. \; \frac{R^{3/4}V^{1/4}}{Z^{1/2}}$$
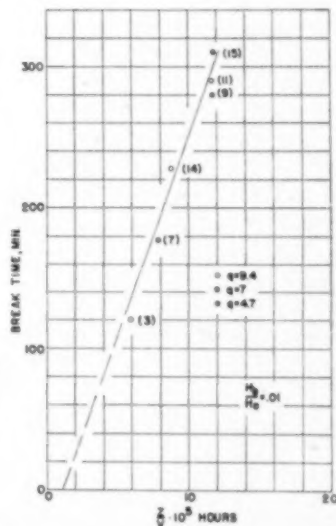
Fig. 8. Relationship between contact time and break time for beds containing 20-24 mesh granules.

Fig. 7. Effect of granule size on break time for beds of 3 in. length; air flow rate 9.4 cu.ft./hr.

In future investigations of rate-controlled reactions, it is suggested that these plots be compared for linearity in preference to the conventional analysis employed here. If one should question Equation (16) then it might be advisable to write it in the more general form

$$K_g a = K^1 \frac{V^n}{R^m} \; ;$$

temperature and pressure constant and determine n and m by applying Equation (19) to a reaction known to be mass transfer controlled. In general one must keep in mind that other reaction mechanisms previously considered in the generalized theory may also be important. It may be too that instead of a single rate-controlling mechanism there may be a superimposition of mechanisms, each one contributing its fair share in which case it would be advisable to combine in the mathematical analysis the appropriate rate equations. In the case of mass transfer followed by internal diffusion one would find that

$$Y = \left[\frac{1}{\left(\frac{R}{\pi}\right)^2 \frac{1}{D_I} + \frac{B}{K_g a}} \right]^{\frac{1}{2}} \left[\left(\frac{B \rho_B}{a V \rho_G}\right)^{\frac{1}{2}} z^{\frac{1}{2}} - t^{\frac{1}{2}} \right] \quad (22)$$

The generalized theory is still applicable and the analysis of data is no more difficult than that already presented.

In the present case it was apparent from X-ray data and the work of Hey (6-8) as well as our own determination of adsorption isotherms that internal diffusion in the granule must be rate-controlling and that the diffusion coefficient for this process must be very small in comparison with that for moisture

Fig. 9. Life-thickness curve for beds containing 20-24 mesh granules.

through air at room temperature which is about 1 sq.ft./hr. Based on Wickes (20,21) work with activated carbon one would expect that for moisture diffusion through the large pores of the carbon the diffusion coefficient would be in the range of 10^{-2} to 10^{-3} sq.ft./hr. In determining the adsorption isotherms it was noticed that activated carbon adsorbed moisture much more rapidly than drierite. Thus in the theoretical analysis of the data which follow the effort is confined to comparing mass-transfer controlled reaction with internal-diffusion controlled reaction both being based directly on the generalized theory previously presented.

Equation (4) and (5) define X and T. Based on the fit of the 2-in. bed a new value of X may be computed for any other bed. This value of X in conjunction with the Schumann-Furnas chart determines the theoretical curve for the other bed. These dashed curves are shown in the figures for representa-tive cases of changes in bed-length velocity and granule size. Neglecting $(S/T)^{\frac{1}{4}}$ in the range of interest introduces appreciable error as far as time is concerned only for the 10-12 mesh granules but even then the error is within 15% at the upper and lower ends of the rising portion of the adsorption wave. As T approaches X this error disappears.

As a basis for comparison it was assumed that mass transfer was controlling even though Figure 8 and the value of D_I suggest that it is not. The starting point was the same theoretical curve for the 2-in. bed just discussed. In order to use the definitions of X and T according to Equations (14) and (15), it was assumed that

$$a = \text{constant} \cdot R^{-1}$$
$$Kg = \text{constant} \cdot V^{.5} R^{-.5}$$
$$X = \text{constant} \cdot V^{-.5} R^{-1.5} Z$$

and $T = \text{constant} \cdot V^{.5} \cdot R^{-1.5} t$. In Figure 2 the 2-in. bed curve is marked MT or ID because it is assumed the same for mass-transfer controlling or internal-diffusion controlling. By means of the definitions the 2-in. bed curve was converted to that for other cases shown in Figures 1 and 4 and labeled MT to distinguish them from ID for the same case. In Figure 1 the dash curves are for 10-12 mesh granules.

The 10-12 mesh curves are somewhat in error for reasons just discussed.

Judging Figure 4 as a typical case one sees that the MT case gives a less satisfactory fit. Actually there is no basis for comparison because if one computes Kga and B from the mass-transfer fit of data one finds that those parameters take on absurd values in order to make the fit possible. The value of B for example approaches zero. Hence one must conclude that internal diffusion must control the reaction.

Beside determining the adsorption kinetics the generalized theory is of value in problems of design. The theoretical adsorption wave for the 9-in. bed is an illustration of this application. All previous runs were concerned with short beds which could be saturated within an 8-hr. day. The internal diffusion theory thus developed was used to predict the adsorption wave for a bed which could be saturated or nearly so in 15-16 hrs., i.e., a 9-in. bed. Figure 6 confirms the success of this application. In fact, it works so well that one is led to wonder why the theory did not do a better job of predicting the 3-in. bed in Figure 2.

Because of its utility it seems advisable to outline the method for predicting the dash curve mentioned in the previous paragraph. The method is based on the Schumann-Furnas chart. Co-ordinates of the chart are H/H_o and T. The chart contains adsorption waves corresponding to values of X. Values of H/H_o greater than .9 are not shown. Thus the problem is to determine which wave contains the point corresponding to $H/H_o = .9$ and $t = 15$ hrs., say. The value, $T = 32.42 \times 15 = 486$, must be used in conjunction with the chart. The wave containing the point (.9, 486), is the one labeled "450." Thus $X = k^2 DZ = 450 = 32.42 \times 18.5 \times Z$ and $Z = .75$ ft. or 9 in.

The above analysis employing the generalized theory has been based on a fit of experimental data obtained for a bed wherein the multiple "humps" in the exhaust curve were not troublesome. A method which can be applied to any exhaust curve consists of plotting

$$\left(2 \frac{H}{H_o} - 1 \right) \text{ vs. } t^{\frac{1}{2}}$$

on arithmetic-probability paper and examining for linearity. This procedure was devised and applied to all the experimental results after this paper had been written. Although it has led to no new conclusions it appears to be a method for data analysis and for that reason is mentioned here.

A detailed examination of the various adsorption waves presented herein reveals several facts of qualitative interest which are not represented by the theory in its present form. The first and most
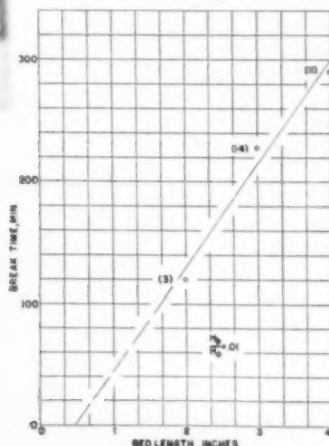
obvious is that some curves exhibit double or triple breaks, i.e., the rising portion of the curve shows two or three humps. These become more prominent at lower flow rates and for longer beds. The cause of this phenomenon might be attributed to the lower packing density of adsorbent at the wall. This would vary from run to run. The higher fluid velocity in this region would cause a segment of bed in contact with the wall to expire prematurely and thus to promote premature leakage of moisture into the effluent. An important point too, is that these effects are exaggerated on a semilog plot.

Other points of interest are those regarding reproducibility of data and the minimum humidity of the exhaust gas. Figure 5 shows that the data vary from run to run for what appears to be the same material and conditions. The difference between runs 10 and 15 may be related to a difference between the amount of desiccant in the two beds. The pressure drop over the bed of run 10 was noticeably greater than that for run 15. This suggests more desiccant and better packing in the bed of run 10. Exact duplication apparently depends upon duplication of the regeneration cycle, the loading and above all maintaining a constant inlet humidity.

The minimum frost point attainable is a direct consequence of the regeneration cycle and operating temperature among other factors. In run 16 (Fig. 1) it was necessary because of the schedule of experiments to leave the charge in the regeneration furnace a half hour longer than the 2 hrs. normally employed. The minimum frost point in this case was less than $-91°$ F. which was the lowest ever obtained during all the experiments. Those concerned with the manufacture of Drierite suggest that $-100°$ F. can be obtained with a 4-hr. 450° F. regeneration cycle. Amero (1) has calculated the minimum frost point as $-87°$ F. This no doubt is based on the normal regeneration cycle of 2 hrs. at 400° F.

Notation

$A =$ cross-sectional area of tower, sq.ft.

$a =$ superficial surface of granule (ignoring pore structure) per unit volume of bed, sq. ft./cu.ft.

$B =$ slope of straight line adsorption isotherm, the formula of which is

$$W_e = B \cdot H_e \text{ for low humidity}$$

$$W_e = B \frac{18.02}{100 \cdot 760 \cdot 28.97} R_{he},$$
dimensionless

$D = \frac{B \rho_B}{aV \rho_G}$, hr./ft.

$D_I =$ average internal diffusion coefficient for water molecules through porous granule, sq.ft./hr.

$G =$ gas mass velocity through bed, lb./(hr.)(sq.ft.)

$H =$ absolute humidity of gas stream (based on bone dry air), lb./lb.

$H_o = H$ at $Z = 0$, lb./lb.

$I_n(Z) =$ Bessel function of order n and imaginary argument

$Kg =$ mass-transfer coefficient for gas phase, lb.(hr.)(ft.²/unit conc.)

$k^2 =$ constant defined in text, 1/hr.

$M_1 =$ moles weight of $CaSO_4 = 136.14$

$M_2 =$ mole weight of $H_2O = 18.02$

$p =$ partial pressure of water vapor in air at temperature, T, and 760 mm. Hg.

$p_o =$ saturation partial pressure of water vapor in air at temperature, T, and 760 mm. Hg. $= 20.1$ at 72° F., mm. Hg.

$q =$ volumetric rate of total gas flow ($q = aVA_T$), cu.ft./hr.

$R =$ average radius of granule assumed to be a sphere, ft.

$R_h =$ per cent relative humidity of gas at T and 760 mm. Hg. total pressure ($R_h = 100$ p/p_o)

$r =$ radial distance from center of granule, ft.

$S =$ variable of integration

$T =$ dimensionless group defined in text

$t = t' - \frac{Z}{V}$, hr.

$t' =$ time during which feed is fed to bed, hr.

$V =$ lineal gas velocity through interstices between granules in bed, ft./hr.

$v =$ summation index

$W =$ moisture content of adsorbent (based on bone dry adsorbent), lb./lb.

$W_e = W$ at equilibrium, lb./lb.

$X =$ dimensionless group defined in text

$Y =$ a variable defined in text

$Z =$ distance from feed end of bed, ft.

$a =$ fraction external voids in bed, cu.ft./cu.ft.

$\rho_B =$ bulk density of dry adsorbent bed (dry basis) $= 65.8$, lb./cu.ft.

$\rho_G =$ density of air stream at temperature T abs., and 760 mm. Hg. $= .0747$ at 72° F., lb./cu.ft.

$\rho_p =$ apparent density of dry porous granule (dry basis), lb./cu.ft.

$\rho_s =$ true density of nonporous dry $CaSO_4 = 185$, lb./cu.ft.

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AN ENGINEER LEARNS TO READ

LAURENCE C. JOHNSTON

Brown Fintube Company, New York, New York

IT all started with a qualitative analysis of myself to see if I had the proper aptitudes, interests and personality factors needed to fulfill the managerial job to which I had recently been promoted. The chart, giving a visual record of the results of the battery of tests, was most encouraging in the factors directly concerned with my job. But in two of the every-day aptitudes, I hit bottom. They were *reading speed* and *reading comprehension*.

What did all this mean? The explanation came from my counselor at the New York University Testing and Advisement Center where the tests were taken. He pointed out that I was still reading word by word so that there was a tendency for mind-wandering instead of mind-concentrating. In other words, I was looking at each individual word as *the, little, red, hen* instead of looking at the group of four words at one glance, as *the little red hen*. Suddenly I realized why I had had so much trouble with school work from beginning to end. Now I knew. I had been reading so slowly that I was easily distracted, and while I looked at words I didn't "see" meaning.

Impressed with the advice I signed up for an evening course at N. Y. U. in remedial reading.

Preliminary Tests

This meant more tests by the Reading Institute to determine my placement in a class that was best suited to my present inability. This battery of reading and comprehension tests showed I wasn't even at the level of a grade school graduate. In fact, I was only equal to the level of a mid-year fourth grader.

Ophthalmograph. Next came ophthalmograph tests where a moving picture was made of the action of the eyes while reading. Contrary to popular belief, your eyes do not move steadily from left to right but in a series of jerks. Your eyes see only while they are fixed on something for a moment or two. They are much like a camera. If you snap the camera while it is moving, you get a blurred picture; but you get a clear one when the camera is held motionless. The ophthalmograph is equipped with two camera lenses, one focused on the right eye and the other on the left. Directed lights are reflected from the center of the eyeballs into the lens making two white streaks appear on the single strip film. Each movement of the eye was shown as it progressed across the page and back, and whenever you stopped to look back. The strip also showed the length of time your eyes stopped to look at a word while you were taking it in. At the end of the moving picture debut, I was given a comprehension test on the not-too-difficult material I was reading while the pictures were being taken.

The summary of this battery of tests showed that I had a one percentile rating, median score of 121, and school grade equivalent of four years, four months. The ophthalmograph test showed I had a speed of 260 words a minute, comprehension of 50%, six regressions (backward eye movements) per 100 words, average span of recognition of 1.25 in. and an average duration of fixation of .28 sec. This proved that specialized training was a must for me.

Mechanical Aids

The schooling consisted of the use of mechanical training aids, class reading, vocabulary-training and homework.

Tachistoscope. The first mechanical aid was the tachistoscope, better known as the "flash meter." The flash meter is essentially a projector with a camera shutter attached. The shutter is arranged so that it can be timed from open down to 1/100 of a second. Work with the flash meter consisted of flashing on the screen digits and phrases with the shutter time being decreased for the same number of digits or phrases or the time remaining the same with more numbers or more words added.

At the start of each class, we were given some warm-up flash-meter work and then we were given a test group to see how much we absorbed. At the first session I saw only a flash of light but as time went on I began to see more and more. As our work with the flash meter progressed, I was able to recognize more numbers—say five or six instead of four—and I showed improvement in recognizing groups of words.

At the start of the word-group work we had only single words flashed on the screen, then two words, and finally we had all kinds of phrases or word groups. It was of particular interest to note that when groups of words were taken from our home-reading assignments and flashed on the screen, some students were able to recognize the phrases at 1/100 of a second. For myself, I recognized only one or two at 1/75 of a second and most all of them at 1/50 of a second.

This proved one thing—you don't have to look at something you already know for a long time in order to recognize it.

That was the start of better reading—looking at groups of words and recognizing them without reading word by word. For instance, take again the phrase "the little red hen." I originally looked at this phrase and saw *the*, then *little*, then *red*, and then *hen*. This meant I spent one second looking at this phrase as my duration of fixation was .28 sec. Now I recognize the phrase as a group of words and see it in a quarter of a second.

Metronoscope. The second mechanical aid to reading improvement was the metronoscope. This device contained a roll much like an ancient scroll. The roll was approximately 36 in. long and the printing on it was large. The roll was allowed to revolve line by line in back of an opening in the machine. The front of the opening was covered by three slides. The slides lowered and then came back up into position one after the other so that you saw a group of words when the first slide dropped, then the next group of words on the line for the second slide and the third group of words when the third slide dropped. The movement of the roll and the slides was all timed together so that a certain reading speed could be obtained by adjusting a dial on the machine.

The metronoscope made it necessary for you to see a group of words and it made you try to recognize them before the slide shut off your vision. Dropping of the slides one after the other made your vision move from left to right with no time allowed for regressions. Each roll covered a certain subject and then questions were presented to see how much of the story was understood. In other words, you had a comprehension test on the material you read. The correct number of questions answered out of the total gave the percentage of comprehension for the subject. The speed of reading for the roll was announced ahead of time so that you knew how fast you were reading that roll.

Harvard Films. The third mechanical training aid was the Harvard films.

These films were on 16 mm. and were run through a normal moving picture projector. The film is made up by photographing a page and then making groups of words stand out from the rest of the material. The page of material photographed is almost faded out, but you can see where sentences and paragraphs begin and end. The first film was made so that it took five fixations to read across the line. Then this was gradually reduced so that at the end there were only two fixations to the line.

The film is designed so that the words are presented in increasing speeds over the series by making larger groups of words stand out and by increasing the speed of the groups across the line. We started at 250 words a minute and at the end of the term were reading 350 words a minute. The Harvard film material is not easy reading so you are pressed to understand what is being shown. Here again a test was given on the material to see how much of it was understood. A series of ten questions, with answers to be selected from one of several, was presented after each film.

Accelerometer. Additional work outside of class time was done on a fourth mechanical aid called an accelerometer or reading rate-controller. With this device you put a book or paper on a stand and lower a framework over it. The framework has a green opaque slide in it and comes down over the reading material at a predetermined rate. The slide, of course, covers everything as it progresses from top to bottom of a page. The object is to keep reading fast enough so as to keep ahead of the shade. It is possible to set this machine so as to read at a rate anywhere from, say, 100 up to 1100 words a minute.

The balance of classwork consisted of timed reading with comprehension tests on the material at hand and a discussion of it. In addition, we were given work on vocabulary-building.

Regressions an Impediment to Adult Reading

It is also necessary to stop regressions (backward eye movements) in order to improve reading. You must keep going forward at all times and if you have missed a word or two, keep on going for you may pick them up as you go along. If you don't realize what the word is by the end of the sentence, don't stop to pick it up until you reach the end of the paragraph. This ruling applies also to words you don't understand. Keep on going to the end of the paragraph. If you still don't know the meaning, look it up at the end of your reading period. So, in order to stop regressions, you

have to keep going and comprehendingly, too.

At this point I would like to digress to relate an incident that happened while I was working with the accelerometer. In the next room was a group of children with their instructor, working on reading improvement. The thin wall with its loose-fitting door allowed their voices to come clearly into the room. At first I was perplexed about getting any work done with all that noise. Then it suddenly dawned that if I were reading correctly, I would not hear the commotion next door. This indeed would be a good test. I set the accelerometer to a rate of 375 words a minute and started reading. After the first few lines I forgot about the kids next door and was concentrating. At the end of the article I took a comprehension test and scored 75%. This taught me that when you concentrate you can blot out distractions.

It is a strange corollary but comprehension does improve with faster reading. School records show that normally a person taking a course has about 25 to 50% improvement in speed and comprehension, with exceptions running to well over 100%.

Purposeful Reading

Here are some simple things to do to improve your reading. First is, reading with a purpose, whether it be frivolous material or a deep subject. Reading for fun or for information will automatically make you concentrate and prevent mind-wandering. Actually, with light material it is easy to concentrate as you are looking for a story to unfold and to see what happens. You become so absorbed you forget what is going on about you. Subconsciously you set up questions in your mind on what is going to happen—and there is the secret of good reading and concentration.

How can this axiom be applied to engineering articles?

First, look at the title and then the sub-titles. This gives a rough idea of the contents. Now, what questions does this raise in your mind? What is the author going to tell or show—has he

indicated a procedure; any tests or other data presented; do you agree initially with his premise; and so forth. With these thoughts or questions in mind, read the first sentence in each paragraph of the article. When you have done that you have skimmed the article. How many questions have been answered? How much more do you want to know?

If the skimming has been sufficient you can let the article rest there, but if you need more information, then set up some more mental questions based on your cursory reading and then read the article through for the data and information you are seeking. When you have done this you have been reading with a purpose.

If you will work on your reading with the idea of recognizing groups of words at one fixation and then try to read at a greater speed than is just comfortable, you will go a long way towards improving your speed and comprehension.

The reading speed will vary considerably with the material at hand. The mean average is 350 words a minute. This can be as high as 1000 words a minute for light, frivolous reading, or can be as low as 150 words a minute for deep and complicated material. Your reading speed should vary with your material. Slow it down for really hard material and speed it up for the light. With practice this plan will improve your reading.

How did I do?

The ophthalmograph showed my speed of reading increased from 260 to 364 words a minute; comprehension from 50 to 80%; regressions dropped from six to four words for every 100 words; average span of recognition went up from 1.25 in. to 1.67 in. Duration of fixation remained at .28 sec. which is normal as you rarely improve upon that, just see more each time you look.

The new battery of comparable tests showed my percentile rating jumped to 86 from 1; median score was raised from 121 to 189; school grade equivalent went from four years, four months to 13 years plus. I was finally back in college as a freshman!

Laurence C. Johnston, associated with the Brown Fintube Co., New York, since 1949, is eastern sales manager. Prior to that, with Process Engineering, Inc., Somerville, Mass., he was engaged in reorganizing the New York sales district. From 1939-1946 he held the title of chief engineer with Patterson-Kelley Co., Inc., East Stroudsburg, Pa., and has been associated also with the Lummus Co., and the Ross Heater & Manufacturing Co. A graduate of the University of Michigan, he holds a degree in mechanical engineering.

CAST ALLOY REFERENCE SHEET

N. S. MOTT, Chief Chemist Metallurgist

The Cooper Alloy Foundry Co., Hillside, N. J.

ALLOY: CORROSION RESISTANT LOW CARBON 25% CHROMIUM 12% NICKEL 3% MOLYBDENUM ALLOY.

APPLICATIONS AND REMARKS: Alloy type 25-12S Mo with its higher chromium and nickel contents gives improved resistance over 18-8S Mo, and is used for more exacting corrosion conditions which are still not so severe as to warrant the use of the relatively expensive FA-20 alloy. It is twice as resistant as 18-8S Mo to hot dilute sulfuric acid and is used extensively in the pulping industry to handle the very corrosive hot sulfite liquor. It may be cast into many types of shapes at an increase in

cost of 7 cents a pound over 18-8S Mo.

DESIGNATIONS: ACI CH-10M.

CHEMICAL COMPOSITION RANGE: C < .10%; Cr 22-26%; Ni 12-15%; Si < 1.5%; Mo 2-3%.

MACHINABILITY: 25-12S Mo machines much better than 25-12S or 18-8S Mo. Its higher strength and hardness and lower ductility and toughness make for better machinability; however, the usual precautions taken for stainless steels such as slow heavy cuts, sharp tool, and

avoidance of glazing work, should be taken.

HEAT TREATMENT: For the best corrosion resistance 25-12S Mo is water quenched from 1950-2050° F. after holding from 1 to 3 hrs. depending upon thickness.

WELDABILITY: For corrosion resistance this alloy should be welded with a similar composition welding rod. All the usual methods may be used. Intergranular corrosion tendency due to carbide precipitation is somewhat obviated but not completely eliminated by its higher chromium content. For the best corrosion resistance therefore the work should be water quenched from 1950 - 2050° F. after welding.

MECHANICAL AND PHYSICAL PROPERTIES:

Tensile Strength, 1000 lb./sq.in.	95
Yield Point, 1000 lb./sq.in.	60
Elongation, %	20
Reduction in Area, %	20
Brinell Hardness	185
Charpy Impact (Std. Keyhole ft.lbs.)	50
Mod. of Elasticity (× 10⁶ lb./sq.in.)	28
Specific Gravity	7.80

Melting Point	2500-2550 ° F.
Specific Heat (B.t.u./(lb.)/° F.) 32-212° F.	0.14
Thermal Expansion (× 10⁻⁶ in./(in.)/° F.) 32-212° F.	7.6
Thermal Conductivity (B.t.u./sq.ft./° F./in.) 32-212° F.	99
Electrical Resistance (Ohms./cir. mil. ft.) @ 32° F.	480

CORROSION RESISTANCE

ACIDS

Acetic 5%, 70 F	E
Acetic 5%, boiling	E
Acetic 80%, 70 F	E
Acetic 80%, boiling	E
Acetic Glacial, 70 F	E
Acetic Glacial, boiling	E
Benzoic 5%, 70 F	E
Boric 5%, 176 F	E
Chromic 10%, 70 F	E
Chromic 10%, boiling	G
Chromic 50%, boiling	F
Citric 5%, 70 F	E
Citric 25%, boiling	E
Citric 50%, boiling	E
Formic 5%, 70 F	E
Hydrochloric 1%, 70 F	E
Hydrochloric 1%, boiling	F
Hydrochloric, 5%, 70 F	F
Hydrochloric 5%, boiling	N
Hydrochloric 25%, 70 F	N
Hydrochloric 25%, 176 F	N
Hydrofluoric 48%, 70 F	P
Hydrofluoric 48%, 176 F	N
Lactic 5%, 70 F	E
Malic all temps.	E
Nitric all concs., 70 F	E
Nitric 65%, boiling	E
Oleic all concs., all temps.	E
Oxalic 5%, boiling	E
Phosphoric 10%, 70 F	E
Phosphoric 85%, 70 F	E
Phosphoric 85%, boiling	N
Stearic concentrated to 200 F	E
Sulfuric 2%, 70 F	E
Sulfuric 2%, 176 F	E
Sulfuric 2%, boiling	E
Sulfuric 5%, 70 F	E
Sulfuric 5%, 176 F	E
Sulfuric 5%, boiling	E
Sulfuric 10%, 70 F	E

Sulfuric 10%, 176 F	E
Sulfuric 10%, boiling	G
Sulfuric 78% (60° Be), 176 F	N
Sulfuric 93% (66° Be), 70 F	E
Sulfuric 93%, 300 F	N
Oleum, 70 F	E
Mixed Acids 57% H₂SO₄, 28% HNO₃, 176 F	E

ALKALIES

Ammonium Hydroxide, all concs.	E
Calcium Hydroxide Sat., 70 F	E
Calcium Hydroxide Sat., boiling	G
Sodium or Potassium, Hydroxide, all concs., 70 F	E
Sodium < 20%, boiling or Potassium	E
Hydroxide 30% boiling	G
Sodium or Potassium Hydroxide, Molten, 600 F	N

NEUTRAL AND ALKALINE SALTS

Barium Sulfide, 70 F	G
Calcium Chloride 5%, 70 F	E
Calcium Sulfate Sat., 70 F	E
Magnesium Chloride 5%, 70 F	E†
Magnesium Sulfate 5%, 70 F	E
Sodium Carbonate, all concs., 70 F	E
Sodium Chloride 5%, 70 F	E†
Sodium Sulfate 5%, 70 F	E
Sodium Sulfide 5%, 70 F	E
Sodium Sulfite 5%, 70 F	E

ACID SALTS

Alum 10%, boiling	E
Aluminum Sulfate 10%, 70 F	E
Ammonium Chloride 5%, 70 F	E†
Ammonium Sulfate 10%, 70 F	E
Ammonium Sulfate 10%, boiling	E†
Ammonium Nitrate, all concs., 70 F	E
Stannous Chloride 5%, 70 F	G†
Zinc Chloride 5%, boiling	E

OXIDIZING ALKALINE SALTS

Calcium Hypochlorite 2%, 70 F	G†
Sodium Hypochlorite 5%, 70 F	G†
Sodium Peroxide	E

OXIDIZING ACID SALTS

Ammonium Persulfate 5%, 70 F	E
Cupric Chloride 1%, 70 F	F†
Cupric Sulfate 10%, 70 F	E
Ferric Chloride 10%, 70 F	F†
Ferric Sulfate, boiling	E
Mercuric Chloride 2%, 70 F	F†
Stannic Chloride 5%, 70 F	F†

WET AND DRY GASES

Chlorine Gas Dry, 70 F	G
Chlorine Gas Wet, 70 F	P†
Sulfur Dioxide Dry, 575 F	E
Sulfur Dioxide Wet, 70 F	E
Sulfur Dioxide Solution, 70 F	G
Sulfur Dioxide Spray, 70 F	F†
Hydrogen Sulfide Dry	E
Hydrogen Sulfide Wet	E

ORGANIC MATERIALS

Acetone, 70 F	E
Acid Sludge (50% H₂SO₄), 200 F	N
Alcohol—Methyl and Ethyl	E
Aniline Hydrochloride, 70 F	P
Benzol, 176 F	E
Carbon Tetrachloride	E
Chloroform	E
Ethyl Acetate, 70 F	E
Formaldehyde, 70 F	E
Phenol 5%, boiling	E
Refinery Crudes	E
Trichlorethylene, boiling	E

PAPER MILL APPLICATIONS

Kraft Liquor	E
Black Liquor	E
Green Liquor	E
White Liquor	E
Sulfite Liquor, 176 F	E
Chloride Bleach	G†
Paper Makers Alum	E

PHOTOGRAPHIC INDUSTRY

Humid Atmospheres	E
Cellulose Acetate	E
Acetic Anhydride	E
Acetic Acid + 1% H₂SO₄	F
Developers	E
Solutions Containing SO₂	G
Silver Nitrate, 70 F	E

FERTILIZER MANUFACTURING

H₃PO₄ + H₂SO₄ + HF	G

PICKLING OPERATIONS

H₂SO₄ + Dichromate, 176 F	E
H₂SO₄ + Hcl, 176 F	N

CORROSIVE WATERS

Acid Mine Water	F
Abrasive Acid Mine Water	F
Sea Water	G
Brackish Water	E

FOOD & ASSOCIATED PRODUCTS

Brines	E
Edible Oils	E
Fats	E
Fatty Acid Distillation	E
Fruit Juices	E
Ketchup	E
Milk Pasteurizing	E
Vinegar and Salt, 70 F	E

No. 7
(SEVENTH OF A SERIES OF TEN)

RATINGS:
E—Excellent resistance. 0.004 max. in. per year of penetration. Corrosion so slight as to be harmless.
G—Good resistance. 0.004-0.012 in. per year of penetration. Satisfactory service expected; at most a slight etch.
F—Fair resistance. 0.012-0.120 in. of penetration per year. Satisfactory service under specific conditions. Light to moderate attack.
P—Poor resistance. 0.120-0.420 in. of penetration per year. Satisfactory for temporary service only.
N—No resistance. 0.420 min. in. of penetration per year. Rate of attack too great for any use.
†—Subject to pitting type corrosion.

CITY OF THE CHATTAHOOCHEE

A NATIONAL meeting of the A.I.Ch.E. will be held March 16-19 in the commercial, industrial and financial dynamo of the Southeast, Atlanta, Ga. Symposia on new equipment used in process industries, chemical market research problems, and practices, and chemical engineering fundamentals will be the highlights of this program. The broad scope of the meeting, both technical and nontechnical, plus the fact that the meeting is in the geographical center of the Southeast, is expected to draw a large attendance of chemical engineers. Headquarters will be Atlanta's Hotel Biltmore.

The Southeastern Section of the A.I.Ch.E. is just being formed and is looking forward to being hosts for the first A.I.Ch.E. meeting in Atlanta for more than 25 years. The charter for the Southeastern Section will probably be granted by the A.I.Ch.E. Council, this year. Local committees have burned the midnight oil to assure members a reception and display of friendship in true southern hospitality. Other local engineering sections, being formed in this territory with a view towards affiliating with the Institute attest to the extent of the industrial development progress in the Southeast.

Atlanta, the capital of Georgia, is nestled in the foothills of the picturesque Blue Ridge Mountains. It is the highest city of major size in the United States, Denver being excepted, being 1050 ft. above sea level; its climate the whole year round is equitable and mild. For the lover of outdoor sports Atlanta provides parks, playgrounds, and 23 golf courses with an annual mean temperature in the sixties. The Chattahoochee River passes Atlanta, on its way to the Gulf, and dredging operations may soon make it navigable to Atlanta.

The city was founded in 1837 by Stephen Harriman Long, an engineer, as a terminal for a railroad. It was first known as Terminus, later as Marthasville, finally Atlanta. Metropolitan Atlanta now has a population of approximately 670,000 people. It is the largest transportation center in the South, the terminus of 15 rail and ten aerial routes. Atlanta's airport is the nation's third busiest. There are 320 scheduled buses in and out of Atlanta daily. It ranks 32nd in the United States in population but ninth in airmail volume. More than 3,300 different commodities are produced in Atlanta, some of the more important being, food products, textiles, chemicals, fertilizer, furniture, paper, paper products, candy and confectionery, printing and iron and steel products. Approximately 3,000 of the nation's leading business organizations have branch offices in Atlanta for manufacturing or warehousing.

Atlanta abounds in points of interest, such as the Cyclorama which is said to be one of the two largest paintings in the world, depicting with three-dimensional effects a scene in the Battle

State Capitol, Atlanta, Ga.

of Atlanta. This million-dollar masterpiece is 50 ft. high and 400 ft. in circumference, weighing approximately 18,000 lbs. Also near Atlanta is Stone Mountain, reported to be the largest single body of exposed granite in the world. A huge Confederate Memorial was begun on its sheer side.

The old southerners made culture and education an art. The Atlanta of today also appreciates and has available the finer things in life; such as, in season, the Metropolitan Grand Opera, Light Opera, and concerts by outstanding artists, and the High Museum of Art containing many famous paintings.

Atlanta has 29 institutions of higher education, some of these being Emory University, Oglethorpe University, Agnes Scott College for Women, and Georgia Tech. There are more institutions of higher learning for Negroes in Atlanta than any other city in the world, with a total of seven negro colleges.

The general theme for the Atlanta meeting is a depiction of the new and the old in the South. The ladies program and the general entertainment for the convention have been based on this motive. Atlanta is one of the truly cosmopolitan centers of the South. Among its residents will be found the descendants of the original settlers, sprinkled with a liberal portion of people from the entire world. This mixture adds both to the culture of the city and to its vitality as to its industrial and distributing center.

The meeting will begin with the usual get-acquainted party for A.I.Ch.E. members on Sunday evening. There will be no charge for the affair, the tickets being secured with registration.

Other group events include luncheons on Monday and Tuesday, a Plantation party on Monday evening and a social hour and banquet for the Tuesday evening attraction.

Georgia Institute of Technology.

Plant Trips

In keeping with the usual program for national meetings, plant trips will be an important feature of the gathering. One afternoon plant visit, will be held on Monday when an opportunity will be given to visit the research laboratories of the Tennessee Corp. Visitors will inspect research laboratories containing special analytical equipment, and the pilot plant which contains complete equipment for carrying out organic sulphonation reaction.

On Tuesday the engineers will have a morning plant visit scheduled to Scripto Inc., manufacturers of mechanical pencils, and the afternoon visit will include the school of chemical engineering of Georgia Institute of Technology and the State Engineering Experiment Station. Two all-day plant trips are offered the final day of the meeting, Wednesday. Both trips will begin at 8:00 in the morning with return at 5:30 in the evening. One will travel to Shawmut, Ala., to the West Point Manufac-

turing Co., for an inspection of the company's new research center and a trip through a mill manufacturing towels. The second trip on Wednesday will be to the Copper Hill Works of the Tennessee Copper Co. Chemical and metallurgical operations involving sulfuric acid, manufacturing of liquid sulfur dioxide, and the smelting of copper will be shown.

Technical Program

Features of the technical program, details shown on pages 18, 24, and 26, are three symposia, and two general sessions. One symposium is titled, "What's New in Process Equipment?" and will be under the chairmanship of Douglas M. Considine of the Minneapolis-Honeywell Regulator Co. This is the first of a project series on the subject, by the Program Committee, and seven papers are being planned to cover mixing, and process instrumentation. The subjects were developed by the chairman after polling a selected group of members as

to what new equipment would be best to review.

Another half-day symposium will be held Wednesday morning on "Chemical Engineering Fundamentals." J. L. Franklin of the Humble Oil & Refining Co. will preside, and the papers will cover Chemical Reaction Kinetics.

Tuesday will be given over to a symposium, "Chemical Market Research Problems and Practices." Richard M. Lawrence, of the Monsanto Chemical Co., will preside, and the eight papers to be given during the course of the day will cover the economic characteristics of the chemical field, functions of market research, sources of figures and specific studies on chemical products. The latter field will be covered by four case histories.

The two general sessions will be under the supervision of H. H. Cudd and H. E. O'Connell.

Ladies Program

Mrs. R. J. Raudebaugh, chairman of the Woman's Committee, has arranged a series of luncheons, parties, and teas for wives of chemical engineers attending the meeting. Tours for the ladies will include Agnes Scott College, Stone Mountain, Emory University, the Cyclorama, and central Atlanta. Techniques in collecting antique porcelain will be demonstrated by Mrs. Jeanette Burns during the Monday afternoon tour. During the tour on Tuesday, ladies will have an 11:00 A.M. coffee hour with Mrs. Blake R. Van Leer, wife of the president of the Georgia Institute of Technology. A tea will be held Wednesday afternoon at Mimosa Hall.

Technical Sessions

Monday Morning

H. H. Cudd, Presiding

Distillation of Hardwood in a Fluidized Bed.—*L. W. Morgan, G. M. Armstrong, Jr., and H. C. Lewis. Georgia Institute of Technology, Atlanta.*

Pipe-Line Design for Non-Newtonian Solutions and Suspensions.—*G. E. Alves, D. F. Boucher, and R. L. Pigford, Du Pont Co., Wilmington, Del.*

The Effect of Shape and Density on the Free Settling Rates of Particles at High Reynolds Numbers.— *E. B. Christiansen and D. H. Barker, University of Utah, Salt Lake City, Utah.*

Design Considerations in the Production of Sulfur from Hydrogen Sulfide.—*E. R. McCartney and A. L. Kohl, The Fluor Corp., Ltd., Los Angeles, Calif.*

Stone Mountain, 16 miles East of Atlanta, is said to be the largest body of exposed granite in the world. Note the Confederate memorial which is being carved out of the rock.
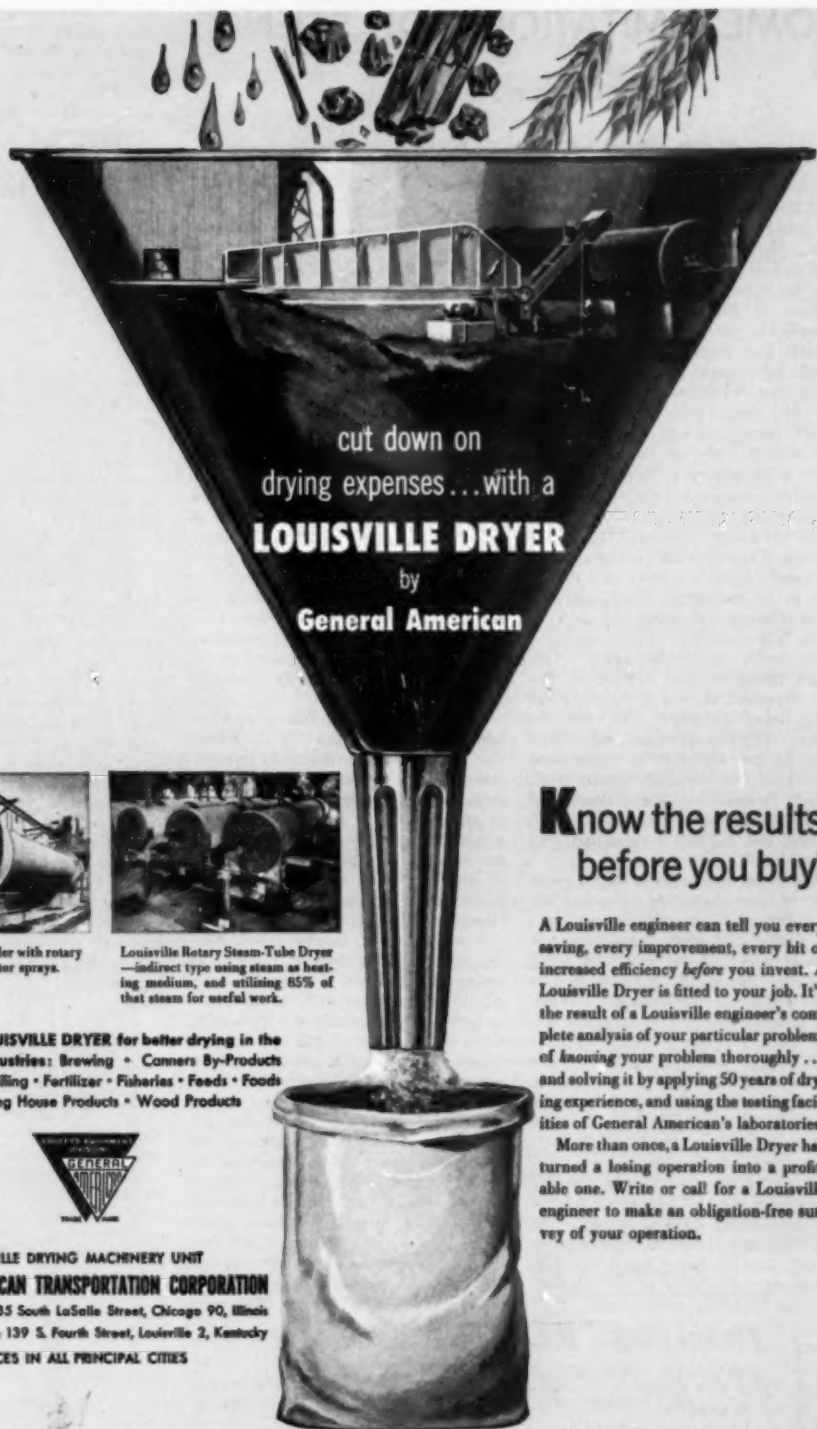
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drying expenses...with a
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Chemical • Distilling • Fertilizer • Fisheries • Feeds • Foods
Mining • Packing House Products • Wood Products
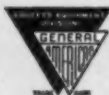
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SOME LIMITATIONS OF SCIENCE

THOMAS E. MURRAY

Atomic Energy Commission, Washington, D. C.

ALMOST two years have passed since I was appointed by President Truman a member of the Atomic Energy Commission. During that time I have been largely engrossed with the problem of fissionable material. The Commission is constantly trying to evaluate and properly apply the latest atomic techniques. The time and study which such evaluations demand, inevitably and recurrently prompt one to ponder about God and the atom; and how society and our individual lives ought to be ordered in this atomic age.

In this connection, I am reminded of a story told by my father years ago. It seems that a much respected Italian immigrant, Pasquale, was accustomed to moan and complain bitterly each day at noon as he opened his lunch box. He would take one look inside and then exclaim, "I'm disgusted—I'm disgusted—peanut butter sandwiches again." One of his fellow-workers listened to this daily complaint as long as he could and finally asked Pasquale what was the matter. Why the continual gripe. Why didn't he ask his wife to make some other kind than peanut butter sandwiches. Pasquale swallowed slowly and finally blurted out, "Because I'm not married, and anyway I make my own sandwiches."

This writer is convinced that a great many of our complaints today are directed toward things of our own making; things that would be different if we only made up our minds to order them so. The world continues to sow wars and reap wretchedness. When wars threaten or come, we complain bitterly. But we live and think things that breed discontent, distrust and fear. We trade in ill-will and hatred. We violate, with abandon, many, if not all, of the laws of the Creator and then call on the bomb to save us from our own folly!

The atomic bomb has, indeed, postponed, and I pray indefinitely, the day of final reckoning. The men of science have contributed much to ward off the great holocaust—how much only history will tell. But let us not forget that sole dependence on science as civilization's savior is bound to prove futile. Life and culture are larger than the expanding universe of science. This is no reflection on science. It is simply another way of saying that science is for man; man is not for science.

We all recognize and deeply appreciate the fact that men of modern laboratories, have exhibited a dazzling ingenuity. Their magnificent contributions touch every phase of living. Through their efforts, yesterday's luxuries have become today's necessities. The list of benefactions is endless; yet their progress has just begun.

An Uncomfortable Presentiment

Scientists have placed in the hands of men power which beggars even the imagination that fashioned the story of Alladin's lamp. If chemical discoveries, machines and atomic energy were all that were needed to make men happy, our earth should be Elysium. Yet for all our power over nature, there's no father, sitting comfortably at home tonight and pondering the welfare of his family, who does not have an occasional dark moment, as the thought of atomic bombardment momentarily intrudes upon his planning.

He knows the tremendous area coverage of the atomic bomb. He also knows that equal area coverage by conventional T.N.T. bombs would be vastly more costly not only in dollars but also in manpower for deliverability. This statement becomes crystal clear to anyone who has been privileged to witness, at close range, an atomic test. I have stood within nine miles of one of our sizeable nuclear explosions.

I stood riveted, dumbfounded, awestricken. I had a feeling I might be looking into eternity. For space is annihilated. Time is measured in millionths of seconds. Temperatures approaching those at the center of the sun are produced. The sensation, emotion and reaction that one feels are difficult to translate into words. There is an empty feeling in the pit of the stomach when, out of the blackness and stillness of the night, a great ball of light plunges into vision. Opaque glasses so dense that ordinary light does not penetrate, seem to melt before one's eyes. You count 1, 2 and 3 and then remove the glasses. Now the fire-ball surpasses summer's midday sun. It represents energies greater than ever before released by man.

The familiar mushroom is there. That might remind you of a highly colored medical picture of the human brain. A rush of heat, like the opening of a furnace door; a crash that seems to break the eardrums and knocks those unprepared off their feet. And all this at nine miles away. The awesome mass, loaded with its cargo of radioactive dust, rises rapidly skyward to sail forever around the world and make its presence known wherever it goes. For some of its particles will give off radioactive rays for 20,000 years or more, others for 40,000 years or more. One might well ask are we not perhaps playing with things that belong only to God.

Weapons—1951

But we can and should get some comfort, in this cold war of nerves from our stockpile of weapons. We are constantly being asked—and rightly so —How do we stand in this atomic race for survival. That's like asking—"Watchman—what of the night?" I can answer: "All seems well." Our search for more ore is proving successful, our efficiency in the use of fissionable material is constantly increasing. Our atomic weapon techniques are improving with each new test, and testing is prerequisite to progress. Unfortunately the Russians know this too, but we hope and pray that we are well in advance of Moscow and that we will be foresighted enough to maintain our lead in all fields of atomic endeavor.

We have recently heard and read much about atomic weapons and secret weapons. Our national habit of reading comic books makes us easy marks for this alluring approach to national security. But it has its tragic side. One might well interpret the news-worthiness of recent speculations about secret weapons as a sign that we have already grown tired of the cold-war struggle and are looking for an easy way out. Let me assure you there is no such primrose path ahead. There are any number of military jobs that cannot be handled by 1951 models of atomic bombs.

What Science Does Not Do

But the scientists have brought us time—time to think clearly—time to reflect—time to act wisely and prudently—time to pray. But the hourglass runs out. It may be later than we think.

Meanwhile what is needed and what I plead for is for all of us to look beyond our stockpile of weapons, atomic submarines, atomic aircraft, chemical discoveries, even beyond science.

Long ago it was recognized that science is a tool. It's a means, not an end or a false god. In order to use this tool well, we must know something of its potentialities, and something of its limitations. As you have heard much

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SOME LIMITATIONS OF SCIENCE

about the prowess of science, it might be well if its limitations were studied.

The most obvious limitation contrasts two kinds of control: control over matter and control over man. Science can give man mastery over matter. It can fail to give man control over himself.

Science has its distinctive method. Like all methods, it has its appropriate and inappropriate applications. It involves experiment with tools, machines, and chemicals. But one cannot, without a kind of sacrilege, experiment with the souls, lives and honor of men.

Then again science never reaches ultimates. It becomes a process of smashing atoms and then of endlessly smashing the parts into which atoms are broken. Thus it never comes to that ultimate particle which is this side of nothing. It "explains" matter by simply dividing it into ever smaller subatomic particles; electrons and protons yesterday; neutrinos and mesons tomorrow. While it explains much, there is a sense in which, we can say, it is forever deferring explanation. It is always postponing the ultimate reason; the element by the molecule; the molecule by the atom; the atom by the nucleus, the nucleus by—"The Good Lord only knows—"

"Surplus of Soul"

Can we get any nearer to the good life by thus constantly raising atomic dust, and giving that dust Greek derivative names mask our ignorances. Progressing, without end, in the knowledge of broken things will never properly answer such fundamental questions as —What is man? What is his destiny? Who is God?

Now that it is possible for us to see farther out into space and deeper into the pointed focus of the atom's nucleus, the body of this world has, as it were, grown larger. For that very reason it needs, in the fine phase of Bergson, a "surplus of soul." Such a surplus cannot be supplied from a laboratory.

We often talk of science as a matter of closed systems. Action equals reaction. Input must equal output. That is why mathematical equations best define the laws of science. One member always precisely equals the other. But life and love are not mere matters of equations. Sacrifice and generosity are what they are precisely because their input does not equal output. To be generous, to be charitable, mean that the reaction is greater than the action. In this field, man can give more than he has received. Indeed by virtue, whether intellectual or moral, man spends but still retains;

T. E. MURRAY

. . . the moral problem of living with the atom . . .

rather, he gains in the act of spending.

Religion and philosophy, on the other hand, can be thought of in terms of open systems. They are not limited to chemical reactions, machines, atomic structures or planetary systems. They are not even bounded by the wanderings of the farthest stars. Nor are they confined within vast areas crossed by the lightning flashes of men's best minds. Religion and philosophy transcend all boundaries. They bring us, in one direction, to God, and the other direction, beyond tomorrow's tiniest division of submicroscopic particles. They take us as far as possibility itself goes. That is why we say they are not closed systems. They are open—open to all reality.

However useful science is to investigate the privacy of tiny chambers called atoms, it is all but useless to investigate the inner and higher life of man. You can't examine free-will in a test tube. Yet, much of what man does for weal or woe springs from this inner life of free choice. Nuclear energy can explode with uncontrollable force. The occasion for its explosion may be controlled by evil or by good men.

Atomic bombs are only dangerous because some atomic men cannot be trusted. Science cannot save men from themselves, any more than society can. Rather, it is individual men who must save society and save themselves. If men will not live by virtue, they may have to die by power! The crisis we face today comes from the greed of men and their will to power regardless of conscience. The responsibility for the crisis is man's refusal to submit his behavior to reason and to reason's God.

The Temptations of Science

In addition to these limitations, there are certain temptations which science does not cause but for which science is an occasion. There is an obvious failing of man in that he is an easy subject of myth-making. He is suggestible in the face of Utopian dreams. He has a natural inclination for comfort and ease. This is the inclination in men which demagogues foster, so that a life of effortless ease might become the goal of men's ambitions. Men want easy money and ready comforts. They want gadgets and conveniences. The glories of science tempts men to use them only for the life without effort, for the life which makes no demands, asks no sacrifice. Others are tempted to make a religion of science. But such a religion becomes a Godless vacuum which substitutes atoms, protons, electrons, for Faith in a Creator.

Yet, precisely because this is not a random world tossed by chance upon the gaming table of space; precisely because all the things that are, were made by God; man's attention must never be so focused on science, as to neglect religion and philosophy which can direct our lives according to right reason and charity. Many of the scientific facts known today were known only to our Creator but a short time ago. That in itself is enough to make man humble.

If men will not clothe the bare framework of science with the warm garments of true humanism, they will end up by making machines their god and mathematics their only dogma. The rising tide of paganism in the Western world will make our civilization cold and ruthless; as cold as interstellar spaces—as ruthless as atoms which smash each other.

Life and culture need modern science; but they need even more the qualities that make life genial and human. Times come for all of us when we must lift our thought not only above the swirl of matter, but also even above plant life and animality. Man needs an appreciation of why he lives and loves. He must be brought into contact with things to live for, and even things to die for.

Glittering galaxies and the dizzying circuits within the atom are not, for all their reality, what a man can really live for or be willing to die for.

Let us never forget that we will have bought our conquest of matter, at too high a price if it robs us of that humility which enables us to detect in every majestic scientific discovery the pathways and the laws marked out by the Divine Architect.

An address given by T. E. Murray at the Awards Banquet of A.I.Ch.E. in Atlantic City, N. J.

CHATTAHOOCHEE

The Prediction of Packed Tower Performance for Vaporization processes from Experimental Data on Flat Surfaces and Wetted-Wall Columns.—*R. J. Stancliff, Jr., James E. Faris, and J. O. Maloney, University of Kansas, Lawrence.*

Monday Afternoon

WHAT'S NEW IN PROCESS EQUIPMENT

Douglas M. Considine, Presiding

Recent Developments in Mixing Equipment.—*Richard D. Boutros, Mixing Equipment Co., Inc., Rochester, N. Y.*

A New Development in the Design of High-Pressure Stuffing Boxes.—*Bruce Alexander, Blaw-Knox Division of Blaw-Knox Co., Blawnox, Pa.*

Developments in the Design of Batch and Continuous Mixing and Kneading Equipment.—*K. A. Mack, Baker Perkins, Inc., Saginaw, Mich.*

New Developments in the Technique and Equipment for Dry Blending.—*Oliver F. Redd, The Patterson Foundry & Machine Co., East Liverpool, Ohio.*

Recent Progress in Process Instrumentation.—*John Procopi, Minneapolis-Honeywell Regulator Co., Philadelphia, Pa.*

Controlled Volume Pumping for Minute Flows of 3 to 3,000 milliliters Per Hour.—*Robert T. Sheen, Milton Roy Co., Philadelphia, Pa.*

A Liquid Dowtherm Heating and Cooling Unit for Controlling Reaction Temperatures.—*J. E. Friden, Standard Oil Company (Indiana), Whiting, Ind.*

Tuesday Morning

SYMPOSIUM ON CHEMICAL MARKET RESEARCH PROBLEMS AND PRACTICES

Richard M. Lawrence, Presiding

Introductory Remarks.— *Richard M. Lawrence, Monsanto Chemical Co., St. Louis, Mo.*

Some Economic Characteristics of the Chemical Industry.— *Maurice W. Leland, Shell Chemical Corp., New York, N. Y.*

Functions of Chemical Market Research.—*Parker Frisselle, The Dow Chemical Co., Midland, Mich.*

Organization and Administration of Chemical Market Research.—*R. B. Wittenberg, General Tire & Rubber Co., Akron, Ohio.*

Sources of Information (Finding the Facts and Figures).— *Richard M. Lawrence, and J. H. Sprague, Monsanto Chemical Co., St. Louis, Mo.*

Tuesday Afternoon

SYMPOSIUM ON CHEMICAL MARKET RESEARCH CASE HISTORIES

Market Survey on Regular Products, (Chlorine and Caustic Soda).—

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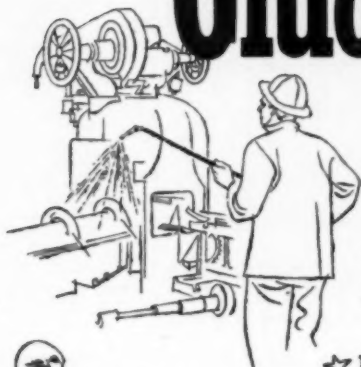
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CHATTAHOOCHEE
(Continued from page 24)

M. E. Clark, Wyandotte Chemical Corp., Wyandotte, Mich.

Market Survey of New Products.—George D. Bieber, Eastern Gas & Fuel Associates, Boston.

Regional Market Survey. — R. H. Ewell, Stanford Research Institute, Stanford, Calif., and M. H. Baker, Chemical Products Distributing Co., Minneapolis, Minn.

Market Survey of An Industry (Paint, Varnish and Lacquer).—C. W. Berl, Hercules Powder Co., Wilmington, Del.

Chemical Market Research—A Career or a Stepping Stone?—S. D. Kirkpatrick, McGraw-Hill Publishing Co., New York.

Wednesday Morning

CHEMICAL ENGINEERING FUNDAMENTALS

J. L. Franklin, Presiding

Synthesis of Methane in a Tubular Reactor.—M. M. Gilkeson, Jr., R. R. White, and C. M. Sliepcevich, University of Michigan, Ann Arbor.

Rates of Alcoholysis and Diffusion in Ion-Exchange Resins. — G. E. Barker and R. R. White, University of Michigan, Ann Arbor.

The Formation of Vinyl Chloride in a Fluidized Catalyst Bed.—Leonard O. Frescoln, Hercules Powder Co., Hercules Experiment Station, Wilmington, Del.

Kinetics of Uncatalyzed Vapor Phase Hydration of Ethylene Oxide.—M. D. Straube and F. Kurata, University of Kansas, Lawrence.

Catalytic Oxidation of Nitric Oxide. M. N. Rao and O. A. Hougen, University of Wisconsin, Madison.

Wednesday Afternoon

H. E. O'Connell, Presiding

Performance of Perforated Plate Distillation Columns.—D. S. Arnold, C. A. Plank and E. M. Schoenborn, North Carolina State College, Raleigh.

The Effect of Column Holdup and Reflux Ratio in Binary Batch Distillation.—Arthur Rose, R. C. Johnson, and T. J. Williams, The Pennsylvania State College, State College.

The Theory of Unsteady State Distillation—the Mathematics of Batch Distillation Calculations.—Arthur Rose and R. C. Johnson, The Pennsylvania State College, State College.

Studies on the Motion of Gas Bubbles in Liquids. Part I.—Velocity and Drag Coefficients of Single Gas Bubbles.—F. N. Peebles and H. J. Garber, University of Tennessee, Knoxville.

Mass Transfer in Liquid-Liquid Extraction.—Stanley Seltzer and Brymer Williams, University of Michigan, Ann Arbor.

ENGINEERING ENROLLMENT UP SURVEY SHOWS BUT SHORTAGE STILL ACUTE

ENGINEERING enrollment in the nation's colleges has increased over the past year but the gap between the supply and the need is becoming wider, according to a report made last month by the U. S. Office of Education and issued jointly with the American Society for Engineering Education.

Only 28,000 engineering students will graduate in 1952 to meet the current demand of from 60,000 to 90,000 engineers. There were 38,000 engineering graduates in 1951; consequently the supply of engineers this year will be 10,000 fewer, a reduction of more than 25 per cent. Since many of the 1952 graduates are either members of ROTC units or are subject to the draft, having been granted deferments to complete their college courses, defense industry is likely to find itself with a deficit of from 40,000 to 70,000 engineers.

A checking of the decline in engineering enrollment is indicated by an increase in the number of freshmen engineering students of 16.2 per cent over 1950. Industry will not, however, have a chance to benefit by this increase until four years hence, the report continued and warned, that there would be "heavy competition from the armed services, since an increasing number of freshmen are joining ROTC units."

The graduation of the last large group of veteran students has dropped the total engineering enrollment 8.4 per cent below that of last year. This decrease, however, compares favorably with the decrease in male student population reported by all higher educational institutions, which is almost 11 per cent smaller than in the fall of 1950.

The increasing desire for graduate training in engineering is reflected by the fact that graduate enrollment is now three times what it was in 1940. Almost 28 per cent of all engineering graduate

ENGINEERING COLLEGE ENROLLMENTS
(U. S. only)
UNDERGRADUATE ENROLLMENT

Year	Freshman	Sophomore	Junior	Senior	5th Year	Part Time and Evening	Total	No. of First Degrees
1940	33,175	24,242	20,120	16,310	985	14,079	108,911	11,358(1939-40)
1947	57,507	71,615	48,227	32,360	1,846	18,616	230,180	18,592(1946-47)
1948	47,672	52,949	59,945	45,695	1,924	17,932	226,117	27,460(1947-48)
1949*	36,508	35,648	41,695	50,991	2,326	13,478	180,646	41,793(1948-49)
1950*	29,394	27,242	30,957	37,707	3,150	14,504	142,954	49,160(1949-50)
1951*	34,147	23,408	24,757	27,820	2,946	15,280	128,367	37,904(1950-51)

GRADUATE ENROLLMENT

	Master's Degrees and Other Pre-Doctoral Degrees					Doctor's Degrees				
Year	Full Time	Part Time	Evening	Total	Master's and Other Pre-Doctoral Degrees	Full Time	Part Time	Evening	Total	Doctor's Degrees
1940	2,003	980	1,599	4,582	1,318(1939-40)	404	179	41	624	108(1939-40)
1947	5,465	3,663	3,515	12,643	3,090(1946-47)	704	784	79	1,567	127(1946-47)
1948	6,136	2,348	4,882	13,366	4,302(1947-48)	1,046	569	454	2,069	252(1947-48)
1949*	6,277	4,056	4,746	15,079	4,763(1948-49)	1,593	793	155	2,541	417(1948-49)
1950*	8,150		7,425	15,575	4,865(1949-50)	2,342		453	2,795	492(1949-50)
1951*	6,878		9,574	16,452	5,134(1950-51)	2,419		456	2,875	586(1950-51)

	1940	1947	1948	1949	1950	1951
Total college enrollment in U. S.	1,490,000	2,333,000	2,410,000	2,456,000	2,297,000	2,116,000
Engineering enrollment in U. S.	113,497	244,390	241,554	198,266*	161,324*	147,694*
Per cent engineering to total	7.6%	10.5%	10.0%	8.0% *	7.0% *	7.0% *

* Includes only E.C.P.D. accredited institutions.

UNDERGRADUATE ENGINEERING ENROLLMENT BY CURRICULA
October 1951
Total Number Enrolled for Their First Engineering Degree

Engineering Curricula Schools Accredited by E.C.P.D.	No. of Schools	1st Year	2nd Year	3rd Year	4th Year	5th Year	Others	Total Men	Total Women	No. 1st Eng. Degrees Conferred 1950-51
Aeronautical	48	1173	796	725	743	64	223	3711	13	1094
Agricultural	36	374	334	367	426	20	2	1522	1	598
Architectural	30	831	925	791	684	229	51	3576	25	1022
Ceramic	14	117	133	130	180	16	8	575	6	258
Chemical	105	2647	2397	2575	2809	408	747	11583	43	3614
Civil	134	4178	3989	4545	5118	423	1491	19701	43	6473
Electrical	134	5167	4928	5172	5931	677	2749	24515	49	8616
Engineering Mechanics	2		7	9	23	....	....	37	1	20
Engineering Physics	12	246	341	368	350	39	22	1358	8	408
General Engineering	27	729	539	562	569	4	637	3046	4	449
Geological*	22	178	235	233	283	5	4	933	4	308
Industrial*	60	794	945	1253	1583	127	365	5057	10	3256
Mechanical	129	5564	5411	5751	6548	846	3014	27080	54	9609
Metallurgical	46	363	512	568	598	48	148	2229	8	797
Mining	31	198	286	340	430	4	9	1266	1	469
Naval Arch. & Marine	4	42	52	52	56	4	7	213	...	78
Petroleum	21	537	565	626	747	6	53	2531	3	846
Sanitary	7	20	34	29	35	1	2	121	1	76
Textile	5	195	147	137	134	....	3	616	...	96
Unclassified	84	10390	669	173	26	....	5723	16766	235	70
Others	36	474	253	353	346	34	21	1483	3	347
Total E.C.P.D.	148	34147	23408	24757	27820	2946	15289	127849	518	37904
Other U. S. Schools	44	5424	3333	2788	2902	268	2915	17587	43	3989
All U. S. Schools	192	39571	26741	27545	30722	3214	18204	145436	561	41893

* Includes administrative engineering, managment engineering, etc.

NEW SO₂ USE

A new method of treating grass silage to retain its nutritional value for cattle was recently announced by Ansul Chem. Co., Marinette, Wis. This method consists of treating fresh-cut grass with liquid sulfur dioxide. The liquid gas is to be marketed to farmers under the name of Grassavar Gas.

Above—A. O. Wingender, technical representative of the company, is shown shooting the sulfur dioxide into the ensiled crop at two-foot intervals at a five-foot depth. Rapidly and completely absorbed by the fresh-cut grass, the sulfur dioxide preserves the silage for indefinite periods. Only five or six pounds of the chemical are required for each ton of grass.

ENG. ENROLLMENT

students are taking their training in electrical engineering. Mechanical engineering accounts for about 17 per cent. while approximately 13 per cent are enrolled in chemical engineering.

The distribution of bachelor's degrees granted in 1951 among the four principal undergraduates engineering curricula was as follows: mechanical engineering, 9,609, electrical engineering, 8,616, civil, 6,473 and chemical, 3,614. The number of graduates in each of the four curricula was considerably lower than the previous year.

Data contained in the report were based upon a survey of engineering schools and colleges made in October, 1951, under the joint sponsorship of the U. S. Office of Education and the American Society for Engineering Education. All institutions listed in the Office of Education Directory of Higher Education which reported that they conferred degrees in engineering during 1950-51 and eight Canadian institutions were requested to supply data.

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BULLETINS

1 • CUT-OUT PULLEYS. Pulleys and couplings which shut off driving motor when overload occurs, by Anchor Steel and Conveyor Co. For use on conveyors. Cut-out breaks circuit when overloaded, resetting is automatic. For speeds up to 2400 rev./min. Bulletin gives engineering information on how to determine size of cut-out, allowable torque, horsepower, chain pull, shear pin strength, etc.

2 • DUST CONTROL. Pulverizing Machinery Co. explanation of Mikro-Collector, a wool felt filter cylinder and reverse jet cleaning ring. Filter rates as high as 30 cu.ft./(min.)/(sq. ft.). Filter medium cleaned by ring traveling up and down filter cylinder forcing a jet of high velocity air through the wool felt dislodging internal dust particles. Standard sizes available from 24- to 36-in. diam. and from 36- to 84-in. length.

3 • PULVA-SIZER. An automatic pulverizer described in a new bulletin from the Pulva Corp. Five standard models using alloy steel rotor shafts and drop forged hammers. Various metals available. Hopper feed via feed screws. Bulletin also explains customer testing service.

4 • CONSTRUCTION TESTING. For the company building new plants U. S. Testing Co., Inc., bulletin on tests made during construction. Covers all building materials as well as soils, piping, paints, etc.

5 • SOLENOID VALVES. For automatic and remote control of liquids and gases, the Automatic Switch Co. has issued a new bulletin. Covers safety, shut-off and trip valves, both manually and electrically reset, pilot valves, explosion-proof, and special devices. Details of construction, illustrations, installations, etc.

Mail Card for more data ⇒

6 • FILTERS AND FILTER PADS. Catalog from F. R. Hormann & Co., Inc., on filtration of chemicals, pharmaceuticals, foods, beverages, and cosmetics. Plate and frame type, asbestos pad filters. Models from 10 in. sq. frames up to 18 in. Pressure- and vacuum-type filters also shown as well as details of laboratory filters, asbestos filter sheets, bottle filters, and portable mixers.

7 • REGULATING VALVES. Double-seated diaphragm regulating valve for control instruments shown on a Leslie Co. specification sheet. For the process industries, unit uses stellited seating surfaces. For use on 3 to 15 lb./sq.in. air supply. Four models of super structures with 50-210 sq. in. of effective area.

8 • HEATER SECTIONS. For heating or cooling air, an L. J. Wing Mfg. Co. booklet on finned heater sections. Copper construction, available in 15 different sizes. Book gives method of selecting proper sizes, dimensions, types, etc.

9 • VERTICAL LEAF-PRESSURE FILTERS. An industrial Filter & Pump Mfg. Co. bulletin on solution clarification. Uses an air manifold for cleaning filter leaves with compressed air and water without removing covers. For use on fruit juices, beverages, chemical solutions, sugar, etc. Models with filter areas from 3½ to 505

sq. ft. Various materials of construction for all parts. Synthetic or standard material filter bags.

10 • MECHANICAL SEALS. A color illustrated brochure of the Garlock Packing Co. showing mechanical seals for centrifugal and rotary pumps operating at speeds up to 3600 rev./min. Unit is a package ready for installation. Three types of mechanical seals are available—package seals, chevron-type seals, and O-ring seals. Data on installation, service records, special applications and data for ordering.

11 • RECORDING OSCILLOGRAPH. For test engineers needing an instrument to record data of static or transient nature, Consolidated Engineering Corp. bulletin on recording oscillograph. Records simultaneously as many as 18 items of test data. Allows wide selection of galvanometers. For use in industries where physical phenomenon is convertible to an electric signal.

12 • SILICONE O-RING. Frederick S. Bacon Laboratories are making O-rings of silicone rubber as hydraulic seals against petroleum and other hydrocarbons. Retain flexibility as low as −65° F. Standard sizes from ¾ to 2¾ in. I.D. Special sizes available. Data sheet available.

Cards valid for only six months after date of issue

Chemical Engineering Progress Data Service

I would like to obtain more information on the items represented by the numbers I have circled.

1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18
19	20	21	22	23	24	25	26	27	28	30	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45	46	47	48	49	55	56	57	58
59	60	61	62	63	64	65	66	67	68	69	70	71	72			

PLEASE TYPE OR PRINT

Name .... Position ....

Company ....

Address ....

City .... Zone ...... State ....

February 1952

DATA SERVICE

14 • VERTICAL PUMP DRIVES. Pacific Gear & Tool Works bulletin on right-angled vertical pump drives. Manufactured in all sizes. For application on horizontal-type prime movers to vertical shaft pumps. Available for speed increasing, no speed change, speed-reducer requirements. Construction features and other data shown.

15 • VITREOUS SILICA TUBING. Data sheet from Thermal Syndicate, Ltd., on vitreosil drawn tubing and rod. Produced in four qualities, sard-surfaced, glazed, translucent and transparent. Sizes, dimensions, prices shown. Resistant to extreme thermal shock, high catalytic and chemical inertness, thermal conductivity, and transmission.

16 • AQUAPULPER. The Cowles Co. describes a new aquapulper for pulping and defibering hard stock. Capacities from 100 to 1100 cu. ft. Capable of processing from 12 up to 100 tons a day in continuous operation. Features high speed, fast dumping and good circulation owing to special tank shape.

17 • LIQUID LEVEL CONTROLLERS. Specification sheet from Minneapolis-Honeywell Regulator Co., on internal and external float cage liquid level controllers for maintaining levels in storage tanks, stills, towers, feed-water heaters, etc. Sizes, specifications, materials, etc.

18 • 19 • ATOM CHART. (18) A vest-pocket chart of the atoms giving atomic number, name, symbol, atomic weights, valance, melting and boiling points. Reverse side has a periodic chart. (19) Data sheet on a new recording spectrophotometer with a range of from 2000 to 12,000 angstroms. Tentative price, $3500. From W. M. Welch Scientific Co.

20 • ALLOYS IN COOPERLAND. A fantasy written in the iambic pentameter of Alice in Wonderland by George Black of Cooper Alloy Foundry Co. Tells with quaint illustration and prose the processes and steps involved in making stainless alloys and stainless alloy castings.

21 • WATER CLARIFICATION. An engineering bulletin on the clarification of water by filtration. Covers the use of diatomaceous filter aids in filtering water, control of pollution, etc. Schematic flow sheets, details of economics of filtration. Great Lakes Carbon Corp.

22 • FABRICATED ALLOYS. Pressed Steel Co. bulletin on industrial equipment from sheet alloys. Covers standard and special bubble caps, welded alloy tubings. Two pages of specifications on alloy bubble caps now available. Explains Le Jons construction for quick assembly and removal of bubble caps.

23 • WALL CHART. A wall chart for engineering design offices on bronze welding electrodes made by Ampco Metal, Inc. Gives trade name, general description, typical applications, mechanical properties, chemical composition, current polarity, color code, and sizes. Electrode selection and preheat chart also.

24 • VARIABLE SPEED DRIVE. A miniature variable speed drive with a push rod ratio control from the Metron Instrument Co. For use on timers, recorders, controllers, computers, etc. Similar to other models by the company. Ratio is variable from 1/6 to 6 by a slight travel of push rod.

25 • BLOWERS AND COMPRESSORS. Extensive bulletin from DeLaval Steam Turbine Co. on new centrifugal blowers and compressors. Data on three types of equipment: the multistage; single-stage end suction, and single-stage double suction. Capacities range from 1000 to 150,000 cu.ft./min. for pressures to 150 lbs./sq.in. and above. Contains application data on blast furnaces, water gas plants, natural gas transmission, air for combustion, agitating, etc. Also data on design and construction, drives, and engineering data on curves, formulas and examples for computing compression of gases and pipe friction.

26 • PIPING MANUAL. Farris Engineering Corp. offers an engineering manual showing the step-by-step calculations in designing a manifold discharge piping system. Of interest to petroleum engineers and safety engineers, showing how safety relief valves offer a controlled relieving point unaffected by a back pressure.

27 • EQUIPMENT CATALOG. For the process industries, a catalog of Esco equipment. Features stainless and high alloy products for special equipment for pulp, paper, chemical food processing, etc. Discussion on corrosion-resistant alloys and various

DATA SERVICE

effects. Shows pipe fittings, valves, screens, conveyors, etc.

28 • GASKET FILE. From the United States Gasket Co. a file folder describing gaskets, sheets, rods, tubing, etc., made of Teflon. Industrial gaskets, metal asbestos, etc., of interest to the process industries.

EQUIPMENT

30 • SURFACE PYROMETER. For measurement of surface temperatures, Pyrometer Instrument Co. new all-purpose pyrometer. A selection of eight types of thermocouples available. Has extension arms, the whole being interchangeable without adjustment or recalibration. Indicator is calibrated in five standard temperature ranges.

31 • AUTOMATIC CLUTCH. For operation on any 7 to 15 h.p. engine and having a normal engagement speed of 1200 rev./min. and disengaging speed as low as 800 rev./min. made by special Tog-o-loc mechanism centrifugally actuated. Clutch drum and pulley assembly ride free during idling periods. Salsbury Corp.

32 • PURGE METER. Brooks Rotameter Co. purge meter available in 2-, 4-, and 6-tube units. For metering and regulating small flows of liquids and gases.

33 • VIBRATOR. A vibrator manufactured by the Martin Engineering Co. for application to large feed hoppers and bins. Uses a 2 in. one-pound ball, pneumatically driven around a stationary, hardened two-rail race. Operates without damage to hopper faces and bins.

34 • COMBUSTION BOATS. A new idea in packaging combustion boats for the analytical laboratory. Preburning unnecessary since boats are fired and sealed in a degreased, unlacquered metal can. Fisher Scientific Co.

35 • PROCESS PUMP. For petroleum hydrocarbons, water, chemicals at elevated temperatures and pressures, a centrifugal operating up to 1000 gals./min. and heads of 625 ft. Temperatures up to 850° F. Various metals, center-line mounting to guarantee proper alignment at any temperature. Peerless Pump.

36 • EXPLOSION-PROOF MOTOR. A combination explosion-proof motor and variable speed drive for use in dangerous locations in production by U. S. Electrical Motors, Inc. New design, self-contained, in one frame on a single base. Controlled drive gives instant change in speeds from 2 to 10,000 rev./min. and ratings from 1 to 20 hp.

37 • BETA EMITTERS. For calibration, Atomic Instrument Co. announces five beta emitters: carbon-14, cobalt-60, thallium-204, bismuth-210 and protactinium-234. For determining beta efficiency of radiation detecting units.

38 • OXYGEN INDICATOR. A new oxygen indicator from Mine Safety Appliances Co. For determining oxygen content in industrial atmospheres used in combustion, metallurgical, and petroleum processes. Reads directly in oxygen concentrations within two per cent of one of four available scale rates.

39 • RESPIRATOR. A new respirator combining ten recently engineered advances by Mine Safety Appliances Co. Breathing resistance is half that of former models. Lower face area eliminates blind spots, filters are quickly changed. Filter is a resin-treated felt which creates a static electrical field to help trap dust particles.

40 • SAFETY GOGGLE. United States Safety Service Co. has designed a new goggle with a bright yellow vinyl frame to comply with the A.S.A. color code. Vinyl optical plastic lens of one piece.

41 • SELECT-O-WEIGH. An automatic cumulative and consecutive weighing unit using a servo-mechanism is announced by Richardson Scale Co. Feature is its applicability to small plants, and a complete flexibility in formula variation for all proportioning operations. Standard-type scale is weighing element with a pendulum-dial scale as a force-measuring component. Master control, with as many dials as ingredients in a formula, controls the weight of materials or each ingredient as it is added. Can provide either delivery of consecutive weights of varying amounts, or accumulation of a total batch of a preselected formula.

42 • TEMPERATURE REGULATOR. A self-operating temperature regulator which allows quick disassembly and cleaning in the field. Visual fingertip dial controls, built in strainers to protect pilot and main valves, stainless steel seats and discs. Farris Stacon Corp. Accuracy to ±1° F. Operates through a single-seated pilot on a vapor flash principle. Sizes available 2 to 4 in. for steam pressures from 10 to 150 lbs./sq.in. gage, temperature controls from 30 to 325° F.

43 • CONTINUOUS VACUUM FILTER. A vapor-tight hood for handling toxic or inflammable products, or materials in an inert or special atmosphere, is shown in a recent design by the Oliver United Filters, Inc., for a continuous vacuum filter. Permits continuous handling of materials formerly requiring batch-pressure filters. Available in chemically resistant construction.

44 • INFRARED SPECTROMETER. A new optical principle to give greater resolution, improved signal-to-noise ratio, and elimination of scattered radiation is announced by the Perkin-Elmer Corp. For use in chemical analyses to determine structure, concentration, and identity of complex compounds.

45 • FLUID PISTON PUMP. A new pump, trademarked Hydrex, devel-

oped by Manton-Gaulin Mfg. Co. Pumping action through two fluid pistons of special hydraulic fluid working above the product to be pumped. By alternate compression and suction in each cylinder, product is made to flow from inlet line to an outlet. For use on corrosive, abrasive, or food products. Manufacturers claim food products, such as strawberries and cherries, are pumped without crushing. Full details available.

46 • COOLING TOWER. A new Marley Co., Inc., double-flow cooling tower for intermediate cooling water capacities. For power, petroleum, gas, chemical and food industries. For a 150-ton unit 7½ ft. tall. One fan is used for two completely open sides. Unit in steel or wood, with asbestos cement board casing.

47 • BLOWERS. A new line of fabricated steel blowers with larger capacity announced by the Lamson Corp. Fabricated steel offers weight saving over past blower construction. Three models offered. Blower outlets may be oriented in any of 14 positions.

48 • EMERGENCY SHOWERS. Logan Emergency Showers, Inc., now producing three basic models of emergency showers for the chemical industry. Models are operated by swinging a gate inside shower. Give complete removal of foreign contamination on the body in 15 secs. or 28 secs., depending on model.

49 • MEASURING CATALYST LEVEL. The Gagetron made by Instruments, Inc., which uses atomic impulses from isotopes to show level of catalyst. Level is measured by number of atomic impulses passing through the counter tube.

CHEMICALS

55 • WEED KILLER. Pacific Coast Borax Co. offers two weed killers for maintenance of road beds, right of way, plant properties, etc. One Borascu is sodium borate ore, the other, polybor-chlorate a combination of borates and sodium chlorate.

56 • CHEMICAL CONTROL UNITS. A general catalogue from LaMotte Chemical Products Co., covering pH equipment and chemicals, chlorine control, soil testing, water, sewage, etc., analysis. Fourteenth edition, gives prices.

57 • WAXES. Two bulletins from the Petrolite Corp., Ltd., one covering emulsifiable waxes, the other microcrystalline waxes. Information on emulsion polishes, suggesting formulas, emulsification procedures, additives, etc. Physical properties given of microcrystalline, wax, solubilities, use in polishes, packaging, and paper manufacturing.

58 • CORROSION-RESISTANT COATING. Carboline Co. adds a new modified phenolic resin to their line of coatings. Applied by brush, spray, or trowel to wood, steel, glass, etc., as protection against organic solvents, caustic soda, dilute acids, etc. Bulletin gives properties, methods of application, surface preparation and corrosion tests.

59 • COLLOIDS. Hydrocolloids from sea plants made by The Seaplant Chemical Corp. For use by the chemical and food industries. Stabilizes emulsions, and foams.

60 • N-ETHYL ETHANOLAMINE. A new ethanolamine from Carbide and Carbon Chemicals Co. bulletin gives chemical properties, shipping data. For use in emulsifying, and the insecticide pharmaceutical, and dyestuff fields.

61 • GEON RESINS. From B. F. Goodrich Chemical Co., a 16-page technical bulletin on compounding polyvinyl chloride. Discusses plasticizer agents, pigments, fillers, lubricants, application.

62 • NOPOL. A high boiling unsaturated alcohol from turpentine, a product of The Glidden Co. Intermediate in the formation of plasticizers, alkyd resin modifier, wetting agents, etc. Bulletin gives physical properties and experimental data.

63 • COATED CONTAINERS. From The Delaware Barrel Co. a descriptive bulletin of polyethylene-lined drums and barrels. For use in the food and chemical field to prevent corrosion of container.

64 • VINYL PRIMER. For use on rusted-steel surfaces, U. S. Stoneware Co. has developed a new primer applied by brush, spray, or dipping. Can be overcoated with any type finish.

65 • CARBONYL IRON POWDERS. A technical manual on iron 99.9% pure, made by the Antara chemicals division. Use in powder metallurgy, catalytic work and as alloying agents. Well illustrated in color gives analytical data, particle-size distributions, plus other physical properties.

66 • ACRYLIC THICKENERS. Aqueous solutions of sodium polyacrylate contain 15% solids for use as stabilizers, protective colloids and thickeners for natural, synthetic rubber and resin latices. American Polymer Corp.

67 • MERCURY. For instruments requiring pure mercury, Bethlehem Apparatus Co., Inc., is now marketing an unbreakable five-pound polyethylene bottle with a flexible dispensing tip for delivery of mercury directly to the instrument.

68 • SORBIT. Data sheet on a sodium alkyl naphthalene sulfonate surface active agent made by the Alrose Chemical Co. Specifications and other data given along with uses in detergents, textiles, polymerization, and fire control.

69 • NAPHTHENATES. Naftone, Inc., offering booklet on Oronite copper and zinc naphthenates as preservatives, for protecting cellulosic materials against mildew, rot and fungus. Applications, formulations, and physical data.

70 • SORBITOL. A complete data book on sorbitol and related polyols of the Atlas Powder Co. History, structure, general properties plus physical data for all the products as well as extensive description, of its use in various industries.

71 • H₂O₂ AND VISCOSE. A bulletin from Buffalo Electro-Chemical Co. gives details on a new application of hydrogen peroxide in the manufacture of viscose. Useful in reducing the aging time of alkali cellulose and in accelerating the ripening of cellulose xanthate.

72 • CLAY IN PESTICIDES. An information bulletin from the Attapulgus Clay Co. of the use of clay as a diluent and carrier in the pesticide field.

let's
take a
closer look
at
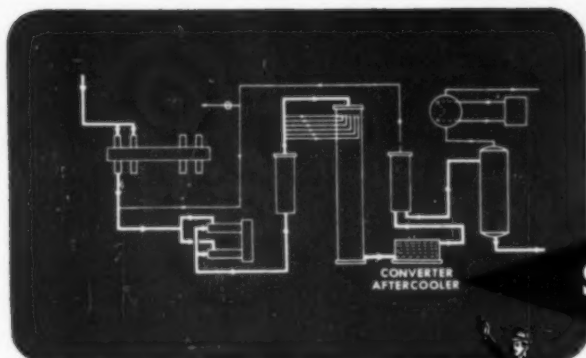
Flow chart of Synthetic Methanol Production, gas synthesis section.

STRESS CORROSION

Here's what happened to Stainless tubing (TYPE 347) when exposed to chloride-bearing bayou water while conveying methanol and unreacted synthesis gases at 300 F and 5000 psi. Note transgranular branching cracks typical of stress-corrosion in pitted stainless steel.

Chloride solutions cause *pitting-corrosion* of stainless steel. Stresses on the material — whether those of construction or high-pressure operation — become localized at the root of the pits. Such stresses may reach sufficient local magnitude to cause stress-corrosion and, eventually, failure.

In this case Croloy 5 tubing was found to have superior resistance to initial pitting and consequently to the whole series of previous troubles.

Whatever the analysis needed, whether stainless grades, intermediate chrome alloys, or carbon steel, "Mr. Tubes" — your B&W Tube Co. representative — can help you solve your problems of tubing selection from B&W's complete range of types, sizes, grades, and finishes. Send for Technical Bulletin 6-E, Properties of Carbon and Alloy Seamless Steel Tubing for High-Temperature and High-Pressure Service.

Here's Croloy 5 tubing, after twelve months in the same service. Note absence of pitting and stress-corrosion. Wall thickness was not appreciably reduced.

THE BABCOCK & WILCOX COMPANY
TUBULAR PRODUCTS DIVISION

General Offices and Plants

Beaver Falls, Pa.— Seamless Tubing; Welded Stainless Steel Tubing
Alliance, Ohio — Welded Carbon Steel Tubing

Sales Offices: Beaver Falls, Pa. • Boston 16, Mass. • Chicago 3, Ill. • Cleveland 14, Ohio • Denver 1, Colo. • Detroit 26, Mich. • Houston 2, Texas • Los Angeles 15, Calif. • New York 16, N. Y. • Philadelphia 2, Pa. • St. Louis 1, Mo. • San Francisco 3, Calif. • Syracuse 2, N. Y. • Toronto, Ontario • Tulsa 3, Okla.
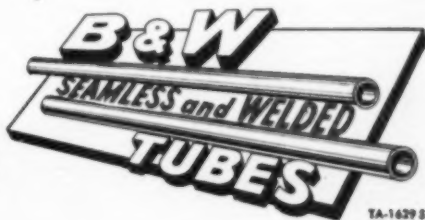
TA-1629 S

Chemical Machinery Operation Improved

Mr. E. J. Kelly, Sales Manager of C. E. Howard Co., manufacturers of storage tanks, agitators and pasteurizers for the chemical and food industries, gives these reasons for using Slo-Speeds on their equipment.

1. *High efficiency of rugged, simplified, precision helical gear system.*
2. *Streamlined design for ease of cleaning.*
3. *Protected housing design.*
4. *Compactness of minimum installation space.*
5. *Positive oil seals.*
6. *Low maintenance.*

STERLING SLO-SPEED
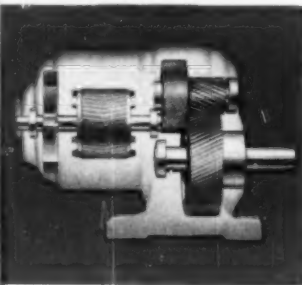
MARGINAL NOTES

News of Books of Interest to Chemical Engineers

On Dangerous Ground

Handbook of Dangerous Materials. N. Irving Sax. Reinhold Publishing Corp., New York. (1951) 848 pp. $15.00.

Reviewed by Reuel C. Stratton, Supv. Chemical Engineering, Travelers Insurance Co., Hartford, Conn.

THIS book of huge proportions is divided into sections making it quite acceptable and easy for the engineer to determine available and essential information.

The section on General Chemicals is extremely good and appears quite complete. Fortunately, the author has included some trade names in addition to chemical designations as well as materials not considered pure chemicals usually. Apparently much effort was put forth in compiling this list which while it reveals certain omissions still fills 410 pages. The list in dictionary form includes properties, health hazards, as well as fire and explosion hazards. This makes it exceptionally useful to an engineer who must obtain ready information about specific chemicals. A quick spot check of the list revealed complete essential information in every case.

Section II covering Explosives is largely in narrative form. It is of important interest at the present time when many engineers are faced with problems in the rearmament program. The section contains a tabulation of explosives and chemical agents with sub-sections on storage, qualifications, destruction, together with good but brief descriptions of the properties of common explosive materials. Safe practices are emphasized throughout. This review shows this to be quite complete for present information. This section if bound by itself would be a useful implement for an engineer entering explosive manufacturing.

Section III covers fungus diseases and fungicides discussing the diseases from an industrial aspect. The information is arranged in a semi-dictionary style and not always alphabetical but it is a useful arrangement as a quick reference source for an industrial physician, nurse or industrial hygienist.

Section IV covers radiation and radiation hazards. It is a good general introduction to the subject. The coverage on means of detection and measuring instruments is good, together with the description of protection against various types of radiation.

Section V covers shipping regulations. It is a review of the I.C.C. Bureau of Explosives Rules. It repeats the general confusion of such rules.

The general index at the end of the book accelerates the finding of most information readily.

Engineers concerned with the manufacture or handling of hazardous materials can look upon it as a sort of Bible, whereas safety engineers and industrial hygienists interested primarily in industrial hygiene and accident prevention may use this as a single book covering many phases of their work. It is a worth-while contribution to the literature and worth of its cost.

Spectra de la Ultraviolette

Ultraviolet Spectra of Aromatic Compounds. R. A. Friedel and Milton Orchin. John Wiley & Sons, Inc., New York (1951) $10.00.

TO the beginner spectrometrist and to the organic chemist with an interest in using ultraviolet absorption spectra as a tool in identifying and estimating quantitatively organic compounds, "Ultraviolet Spectra of Aromatic Compounds," by R. A. Friedel and Milton Orchin (John Wiley, publisher) should prove helpful. The present catalogue is a "modest start in the systematic collection of the ultraviolet spectra of this class of compounds."

Approximately 600 graphs showing the wavelengths in Angstroms of the various spectra are well spaced on the pages which are spiral bound so that they may be removed and superimposed for more accurate comparison. As expressed in the authors' purpose of the collection, half of these spectra have been taken from the literature and have been transformed, where necessary, into a consistent method of plotting. The work of certain chemists active in the field here and abroad was consulted and compounds deemed of general or specific interest were selected. With the material printed on only one side of the page such a comparative study is made easy. After removal from the binding, the graphs can be inserted in a conventional three-ring binder.

The coverage of the book is wide including such chapter headings as the following: Spectrometric Nomenclature

MARGINAL NOTES
(Continued from page 38)

and the Absorption Law for Solutions: Instruments and Experimental Procedure; Theoretical Aspects of Ultraviolet Absorption Spectra; Use of Ultraviolet Spectra in Qualitative Analysis; Quantitative Analysis; Use of the Catalogue, and Collection of Spectra, Name Index of Spectra, and Formula Index of Spectra.

If one cannot tell about a book by its cover at least the reader of this one should be attracted by its appearance both out and in. The price of the book is $10 and it is $10 worth.

Papers for the Well Informed

The Journal of the Institute of Metals. Vol. LXXVII. N. B. Vaughan, Editor. Institute of Metals, London. (1950) 676 pp.

Reviewed by J. D. Stett, Chmn., Dept. Mechanical Engineering, Rutgers University, New Brunswick, N. J.

THIS is a worthwhile collection of technical papers covering a wide range of metallurgical topics, many with such details as to be of interest only to those well informed along specialized branches of the field. This is not a book one would acquire for his general library, but rather a source of information on such specific topics as Stress Corrosion of Aluminum—7% Magnesium Alloy or Corrosion and Related Problems in Sea-Water Cooling and Pipe Systems in H. M. Ships. Several papers are of general interest to all metallurgists and chemical engineers and are well written. One paper, Pitting Corrosion in Copper Water Pipes Caused by Films of Carbonaceous Material Produced During Manufacture, reveals that pitting in cold water copper pipe lines was due to carbonaceous films formed from drawing lubricant residues during the annealing of the pipe.

A total of 28 technical papers is presented, together with discussions and an author index. Included is a Presidential Address, and report on Institute meetings.

Books Received

Chemistry . . . Key to Better Living. Diamond Jubilee Volume of American Chemical Society, Washington, D. C. (1951) 244 pp.

Biological Effects of External Beta Radiation. National Nuclear Energy Series. Raymond E. Zirkle, Editor. McGraw-Hill Book Co., New York. (1951) 242 pp. $3.25.

Organic Reactions. Vol. VI. Roger Adams, Editor in Chief. John Wiley & Sons, Inc., New York, N. Y. (1951) 517 pp. $8.00.

CARBON DISULFIDE MADE
AT PENN YAN PLANT
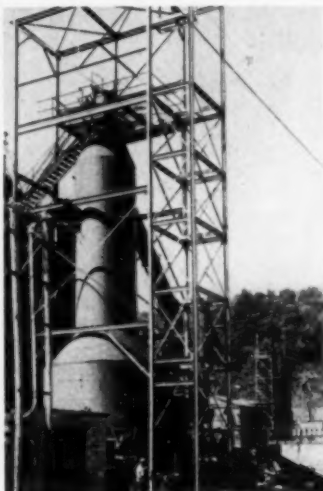
A new electrothermal furnace for the
manufacture of carbon disulfide at the
Penn Yan (N. Y.) plant of Taylor chemi-
cal division of the J. T. Baker Chemical
Co. is shown above. The plant is the first
to produce carbon disulfide in com-
mercial quantities by an electrothermal
process using as raw materials sulfur
and charcoal. The expansion at Penn
Yan is part of Baker's $3,000,000 mod-
ernization program started in 1950, and
scheduled to be completed this year. In-
cluded in the program is a unit to recover
sulfur from waste gases.

APPLIED MECHANICS IN
ISTANBUL IN AUGUST

The Eighth International Congress
for Applied Mechanics will be held at
the University of Istanbul, Istanbul,
Turkey, Aug. 20 to Aug. 28, 1952.

The Congress is a voluntary associa-
tion of individual scientists organized
every four years by a local committee
named by a continuing International
Committee. American participation in
the forthcoming Congress is being or-
ganized by the U. S. National Commit-
tee on Theoretical and Applied Me-
chanics, a joint committee of A.S.M.E.,
A.I.Ch.E., and other technical societies.
H. L. Dryden, director, National Ad-
visory Committee for Aeronautics, is
chairman, and C. E. Davis, Secretary of
A.S.M.E., is secretary.

Membership in the Congress is open
to all individuals interested in applied
mechanics. Each member may present
two 15-minute papers. Abstracts not ex-
ceeding 400 words in length must be
submitted not later than June 1, 1952,
on forms which may be secured from
the Secretary of the Congress. Pro-
ceedings will be published.

PERKIN MEDAL TO BURNS

A prediction that the chemical industry would be rivaled in size in the future by a new electronics industry based upon the transistor, a new device no larger than a garden pea, was made by Robert M. Burns, chemical director of the Bell Telephone Laboratories, in accepting the 46th Perkin Medal last month.

Dr. Burns said, "the wave of the future is an electron wave and can best be seen by choosing a ball composed of a single crystal of the chemical element germanium. For then one might see the rise of a new electronics industry based on the transistor—an electronic device (employing germanium) smaller than a garden pea that performs most of the functions of a vacuum tube, and some that a vacuum tube does not, and operates at powers one ten thousandth of that required to heat the filament of the smallest vacuum tube."

Dr. Burns saw a need for enlargement of our programs of training young men. He said:

The demand for chemists will continue to grow. This imposes a need for wider breadth of specialization in chemical training and perhaps more chemical courses in the nonchemical curricula. The present production of chemists with the Ph.D. degree might be sufficient for the research needs of industry if they were all qualified for research work and were so used. Recent scrutiny of the character of training at the doctoral level may bring about improvements by encouraging greater discrimination in the selection of men to be trained and by providing more practice in research during the course of training.

Dr. Burns' accomplishments include the control and prevention of corrosion; development of primary batteries, storage cells (cadmium-lead) and electrolytic capacitors (employing aluminum and tungsten); the development of ceramic and high polymer insulating and structural materials, and the artificial growth and utilization of large piezoelectric crystals for the control of electronic circuits.

The Jury of Award of the Perkin Medal consists of representatives of the American Chemical Society, the American Institute of Chemical Engineers, the Electrochemical Society and the American Section of the (French) Societe de Chimie Industrielle, in addition to officers of the American Section of the Society of Chemical Industry, under whose auspices the medal is awarded. Dr. Gustavus J. Esselen was 1951 chairman of Jury of Award.

NEWS

M.C.A. OPPOSES MILLER BILL

AN all-day conference on chemicals in foods, sponsored by the Manufacturing Chemists' Association last month in New York, resulted in several proposals from the organization for strengthening the powers of the Food and Drug Administration. At the same time the group took the position that the Miller bill, introduced last year by Representative Miller, a member of the Delaney Committee, to control chemical additives to food, should not be passed.

The M.C.A. said that present legislation is sufficient to cope with any problems that arise in connection with chemicals in food, and that only one 'area exists where the present law needs strengthening; that of assuring that advance information of proposed new uses is supplied by industry to the Food and Drug Administration. The M.C.A. suggested that new legislation of the following provisions, be enacted: That no new use of a chemical additive for food be made until 60 days after a notice of such use has been filed by either a chemical manufacturer or a food processor with the F.D.A. The notice shall report the pharmacological and toxicological data, the known composition of the chemical additive, a method for determination of the amount of the additive in food and directions for the use of the chemical additive; the notice to be accompanied by samples of the chemical additive, and that within the 60-day period the F.D.A. be given the authority to request a hearing on its use.

The chief objection of the M.C.A. to the Miller bill is that it requires a positive F.D.A. approval for every case where a chemical is added, and at the same time, gives F.D.A. advance information on all proposed new uses. This, argued the manufacturers, gives the F.D.A. a life and death jurisdiction over new ideas.

During the day, C. W. Crawford, Commissioner of Food and Drugs of the Federal Security Agency, and chiefly responsible for the Miller bill, spoke to the group and presented his viewpoint. "The Miller Bill, H.R.3257," said Mr. Crawford, "is patterned after existing sanctions of the FDA law on drugs." He drew examples from existing practice to show how it would operate. F. M. Peters, Jr., vice-president of the Quaker Oats Co., in charge of chemical research, was also a speaker and said that the danger in the act was that the life and death authority of the commissioner of the Food and Drug Administration would stifle research.

READCO

CHEMICAL EQUIPMENT

a matter of men and machines

Read Standard's ability to manufacture the many complex types of equipment required by the processing industries is as much a matter of men as machines.

READ STANDARD
CORPORATION

POWER FROM BREEDER PILE

Small amounts of electric power have been produced from heat energy released in the operation of the experimental breeder reactor, recently completed at the National Reactor Testing Station in Idaho, it was announced late in December by A. Tammaro, manager of the Chicago operations office of the Atomic Energy Commission.

In a trial run on Dec. 21 and 22, 1951, electric power of more than 100 kw. was generated and used to operate the pumps and other reactor equipment and to provide light and electrical facilities for the building that houses it. The heat energy generated was removed from the reactor by a liquid metal at a temperature high enough to generate steam to drive the turbine.

The principal function of the breeder reactor is the long-range goal of converting nonfissionable material into fissionable material more rapidly than nuclear fuel is consumed, a process that would contribute to expansion of the current atomic weapons program.

The power generation phase is incidental but is being carried out to secure experimental information on the handling of liquid metals at high temperatures under radioactive conditions and on the extraction of heat from a reactor in a useful manner. The system at the breeder reactor can never generate large amounts of electric power but it does provide a useful tool for carrying out such experimental studies.

NEW PLANT FOR STERLING

Sterling Electric Motors, Inc., started production in a new $2,000,000 plant at Van Wert, Ohio, last month. The plant was built to help speed the national defense program.

Sterling manufactures variable speed and geared electric motors and has plants in Los Angeles, New York, Hamilton, Canada, and Santiago, Chile.

ADDITION TO CHEM. ENG. STAFF OF UNIV. PA.

The department of chemical engineering at the University of Pennsylvania, Philadelphia, Pa., has been augmented by the appointment of P. Frank Hagerty. Mr. Hagerty's undergraduate and M.S. training was obtained at the Massachusetts Institute of Technology, Cambridge. Following two years at Eastman Kodak Co. he recently completed his graduate work at Yale.

E.C.P.D. ANNUAL REPORT

The 19th (1951) Annual Report of the Engineers' Council for Professional Development is now available for fifty cents from E.C.P.D., 29-33 West 39th Street, New York.

COMBUSTION CATALYST FOR GASOLINE ENGINES

A preliminary announcement was made last month by Associated Development and Research Corp. of a new combustion catalyst which, it is claimed, will eliminate carbon formation and knock in gasoline engines. The announcement was made by Robert S. Wallach, president of the corporation and Dr. Sophia Berkman, inventor of the new catalyst as well as a new catalytic theory which she reviewed briefly at the meeting.

In the new process a synthetically compounded catalyst of "natural minerals is cast in the cylinder head or piston of the automobile." It is this catalyst, Mr. Wallach said, which increases combustion and decreases the formation of carbon.

According to the company the new catalyst, when tested in C.F.R. engines, increased 60 octane gas to 80 octane and 80 octane gasoline to 100. The company has run more than 200 tests, Wallach revealed, some as long as 100 hrs. in length.

Associated Development and Research Corp. was formed in 1945 for general development work, and is the parent organization of the Transonic Corp. and General Computing Corp. Backing the organization is J. S. Rockefeller, T. T. Scudder of Scudder, Stevens & Clark, Kenneth Baxter president of Deep Rock Oil Corp. and others.

The catalyst is put in the form of studs in the metallic portion of the cylinder head or piston. The decrease in carbon formation was said by the company authorities to be quite noticeable.

CORROSION SYMPOSIUM

The local sections of A.I.Ch.E. in the area of Akron, Ohio, have scheduled a symposium on Corrosion to be held in Akron, April 21, 1952. Co-chairmen are R. C. Stell and W. M. Otto. Watch for details in the March issue of "C.E.P."

LONGVIEW PLANT OF TEXAS EASTMAN OPERATES

Operations at the Longview (Tex.) plant of the Texas Eastman Co. began last month to produce ethanol, *n*-butyraldehyde and isobutyraldehyde from natural gas and propane. The plant, located on a 2400-acre site, is being operated by Texas Eastman Co., a division of Eastman Kodak Co. Original research on the production problem was done by another Eastman subsidiary, Tennessee Eastman.

FUTURE MEETINGS AND SYMPOSIA OF A.I.Ch.E.

Chairman of the A.I.Ch.E. Program Committee

Walter E. Lobo, The M. W. Kellogg Co., 225 Broadway, New York 7, N. Y.

MEETINGS

Atlanta, Ga., Atlanta Biltmore Hotel, Mar. 16-19, 1952.
Technical Program Chairman: H. E. O'Connell, Ethyl Corp., Box 341, Baton Rouge, La.

French Lick, Ind., French Lick Springs Hotel, May 11-14, 1952.
Technical Program Chairman: W. W. Kraft, The Lummus Co., 385 Madison Avenue, New York, N. Y.

Chicago, Ill., Palmer House, Sept. 11-13, 1952.
Technical Program Chairman: D. A. Dahlstrom, Chem. Eng. Dept., Northwestern University, Evanston, Ill.

Annual — Cleveland, Ohio, Hotel Cleveland and Carter Hotel, Dec. 7-10, 1952.
Technical Program Chairman: R. L. Savage, Dept. of Chem. Eng., Case Inst. of Tech., Cleveland 6, Ohio.

Biloxi, Miss., Buena Vista Hotel, Mar. 8-11, 1953.
Technical Program Chairman: Norman A. Spector, Vitro Corp., 233 Broadway, New York 7, N. Y.

Toronto, Canada, Royal-York Hotel, April 26-29, 1953.
Technical Program Chairman: Brymer Williams, Dept. of Chem. and Met. Eng., University of Michigan, Ann Arbor, Mich.

San Francisco, Calif., Fairmont and Mark Hopkins Hotels, Sept. 13-16, 1953.
Technical Program Chairman: R. W. Moulton, Head, Dept. of Chem. Eng., University of Washington, Seattle, Wash.

Annual—St. Louis, Mo., Hotel Jefferson, Dec. 13-16, 1953.

SYMPOSIA

New Types of Equipment for Use in Process Industries
Chairman: D. M. Considine, Market Extension Div., Ind. Div., Minneapolis-Honeywell Regulator Co.,
7th and Grange Sts., Philadelphia. Pa.
Meeting—Atlanta, Ga.

Market Research
Chairman: R. M. Lawrence, Monsanto Chem. Co., St. Louis 4, Mo.
Meeting—Atlanta, Ga.

Vacuum Engineering
Chairman: W. W. Kraft, The Lummus Co., 385 Madison Avenue, New York, N. Y.
Meeting—French Lick, Ind.

Distribution of Chemicals
Chairman: D. A. Dahlstrom, Northwestern University, Evanston, Ill.
Meeting—Chicago, Ill.

Applied Thermodynamics
Chairman: W. C. Edmister, California Research Corp., Richmond, Calif.
Meeting—Cleveland, Ohio

Human Relations
Chairman: R. L. Demmerle, General Aniline & Film Corp., 230 Park Ave., New York, N. Y.
Meeting—Cleveland, Ohio.

Modern Statistical Methods in Chemical Engineering
Chairman: C. Daniel, Engineering Statistician, 116 Pinehurst Ave., New York 33, N. Y.
Meeting—Cleveland, Ohio.

Filtration
Chairman: F. M. Tiller, Dir., Div. of Eng., Lamar State College of Technology, Beaumont, Tex.
Meeting—Cleveland, Ohio

Chemical Engineering in Hydrometallurgy
Chairman: John D. Sullivan, Battelle Memorial Institute, Columbus, Ohio.
Co-Chairman: John Clegg, Battelle Memorial Institute, Columbus, Ohio.

Fluid Mechanics
Chairman: R. W. Moulton, Head, Dept. of Chem. Eng., University of Washington, Seattle, Wash.

Authors wishing to present papers at a scheduled meeting of the A.I.Ch.E. should first query the Chairman of the A.I.Ch.E. Program Committee, Walter E. Lobo, with a carbon copy of the letter to the Technical Program Chairman of the meeting at which the author wishes to present the paper. Another carbon should go to the Editor, F. J. Van Antwerpen, 120 East 41st Street, New York 17, N. Y. If the paper is suitable for a symposium, a carbon of the letter should go to the Chairman of the Symposia, instead of the Chairman of the Technical Program, since symposia are not scheduled for any meeting until they are complete and approved by the national Program Committee. Before authors begin their manuscripts they should obtain from the meeting Chairman a copy of the Guide to Authors, and a copy of the Guide to Speakers. The first book covers the preparation of manuscripts, and the second covers the proper presentation of papers at A.I.Ch.E. meetings. Presentations of papers are judged at every meeting and an award is made to the speaker who delivers his paper in the best manner. Winners are announced in *Chemical Engineering Progress*, and a scroll is presented to the winning author at a meeting of his local section. Since five copies of the manuscript must be prepared, one should be sent to the Chairman of the symposium and one to the Technical Program Chairman of the meeting, or two to the Technical Program Chairman if no symposium is involved and the other three copies should be sent to the Editor's office. Manuscripts not received 70 days before a meeting cannot be considered.

NEWS

LONGVIEW PLANT OPENS

The two main streams of raw materials into the plant are natural gas and propane. The natural gas is reacted at high temperatures with carbon dioxide and steam to form a synthesis gas and hydrogen for subsequent hydrogenation processes. The mixture of synthesis gas is reacted catalytically with propylene obtained by cracking propane, to form a mixture of aldehydes. The aldehyde mixture is refined into the two main products *n*-butyraldehyde and isobutyraldehyde. From the propane cracking process two main products are obtained, propylene used in the Oxo reaction to obtain crude aldehydes, and ethylene which will form the basis for production of ethyl alcohol. The alcohol plant is not yet in production, but it is expected to be on stream in April.

The production of *n*-butyraldehyde will be split three ways, a portion to be sold as the aldehyde, a portion shipped to Kingsport, Tenn., where it will be converted to alcohol and butyric acid for use in manufacturing cellulose acetate butyrate and Tenite plastic, and a portion converted to 2-ethyl hexyl alcohol for use in manufacturing dioctyl phthalate in Kingsport.

The isobutyraldehyde production will also be split three ways, one part will be available to industry as the aldehyde, another part will be converted to the alcohol, and a part will be converted to the acetate. Tests made in substituting the isobutyl alcohol and acetate in lacquer formulations currently using the *n*-butyl solvents show great promise. The ethyl alcohol produced in Texas will be shipped to Kingsport for conversion into acetic acid, acetic anhydride and solvents such as ethyl acetate and isopropyl acetate.

The Texas Eastman plant is located about five miles from Longview on the banks of the Sabine River in Harrison County. The Sabine is a small stream during most of the summer months, and because of this, Eastman has created a 300-acre lake on its property by erecting a dam across a small creek. The lake is in the shape of a horseshoe and measures about one and one-half miles around from tip to tip. Into one end of the lake river water is pumped as needed. Also into this end of the lake condenser water is discharged from the plant. Water for plant use is taken from the bottom of the other end of the lake. The lake thus provides a settling and cooling basin which will be of particular importance in the summer months when the Sabine is low, full of silt and its water at an elevated temperature.

CANDIDATES FOR MEMBERSHIP IN A.I.Ch.E.

The following is a list of candidates for the designated grades of membership in A.I.Ch.E. recommended for election by the Committee on Admissions.

These names are listed in accordance with Article III, Section 7, of the Constitution of A.I.Ch.E.

Objections to the election of any of these candidates from Active Members will receive careful consideration if received before March 15, 1952, at the Office of the Secretary, American Institute of Chemical Engineers, 120 East 41st., New York 17, N. Y.

APPLICANTS FOR ACTIVE MEMBERSHIP

Barker, Walter E., *Nutley, N. J.*
Barrett, Fred O., *Glendale, Ohio*
Bechtel, Robert J., *Parlin, N. J.*
Blatchford, J. W., *Charleston, W. Va.*
Bonow, S. Crawford, *Wood-Ridge, N. J.*
Brantley, Francis E., *Laramie, Wyo.*
Britton, Orson J., *Rochester, N. Y.*
Bunzl, Rudolph H., *Concord, Calif.*
Chinn, Harry W., *Borger, Tex.*
Clark, Melvin E., *Wyandotte, Mich.*
Cowan, James C., *Barberton, Ohio*
Davidson, Donald D., *Walnut Creek, Calif.*
Drew, David A., *Wilmington, Del.*
Evans, G. E., *Monaca, Pa.*
Fisher, T. W., Jr., *Elverson, Pa.*
Ford, Francis L., *E. Paterson, N. J.*
Friedland, Daniel, *Plainfield, N. J.*
Gross, Charles N., *Richland, Wash.*
Hamilton, George B., *Barcelona, Venezuela*
Hill, Howard W., *Concord, Calif.*
Houser, Howard E., *Midland, Mich.*
Hunter, R. Q., *Bridgeville, Pa.*
Kandiner, Harold J., *Philadelphia, Pa.*
Kean, Robert H., *Richmond, Va.*

Kridel, Donald J., *Rochester, N. Y.*
Kunreuther, F., *Houston, Tex.*
Laugel, Roland L., *Ho-ho-kus, N. J.*
Mancke, Edgar B., *Bethlehem, Pa.*
Mockridge, Paul C., *Mt. Vernon, N. Y.*
Nelson, Karl J., *Cranford, N. J.*
Ogden, Robert P., *Wyandotte, Mich.*
Preble, Bennett, *Los Angeles, Calif.*
Reiss, Carroll R., *Cheviot, Ohio*
Richardson, Dean E., *Texas City, Tex.*
Schall, Josef W., *Marcus Hook, Pa.*
Scrimgeour, Robert B., *Hatboro, Pa.*
Shockley, Gilbert R., *Salt Lake City, Utah*
Taylor, Dwight K., *Chicago, Ill.*
Warrick, H. R., *Pleasantville, N. Y.*
Whelan, Thomas, Jr., *Houston, Tex.*
Wrigley, C. Davis, *Media, Pa.*
Yeager, Harold, *St. Louis, Mo.*

APPLICANTS FOR ASSOCIATE MEMBERSHIP

Crooks, William R., *Mt. Vernon, Ohio*
Gardner, Ross S., *Troy, N. Y.*
Holmes, Robert E., *Delaware, Ohio*
Levine, I. Eagle, *Beaver, Pa.*
Scholl, Donald F., *Metuchen, N. J.*
Shanta, Charles, *McKees Rocks, Pa.*
Sokol, Benjamin, *Valley Stream, N. Y.*
Wall, C. J., *Westport, Conn.*
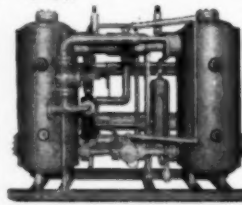
APPLICANTS FOR JUNIOR MEMBERSHIP

Adams, Quandt, *Lorain, Ohio*
Andersen, Bjorn A., *Bloomfield, N. J.*

Beyler, Dudley, *Drexel Hill, Pa.*
Blyth, Randolph C., *Aruba, N. W. I.*
Bondor, Frank S., *Marcus Hook, Pa.*
Bowen, David G., Jr., *Orange, N. J.*
Boyd, Austin P., *Texas City, Tex.*
Brinkman, Ernest J., *Texas City, Tex.*
Brown, Lee F., *Marcus Hook, Pa.*
Buividas, L. J., *New York, N. Y.*
Cardello, Ralph A., *Roselle Park, N. J.*
Cohen, Stanley, *Nashville, Tenn.*
Costine, Raymond L., *Wilmington, Del.*
Damico, Frank A., *West Reading, Pa.*
De Friece, Allen N., *La Porte, Tex.*
Durland, Wm. R., *Trona, Calif.*
Eboch, Richard F., *Camden, N. J.*
Frank, Sidney M., *West Orange, N. J.*
Fuller, William H., *Wilmington, Del.*
Geist, Joseph E., *Bloomsburg, Pa.*
Goding, Arthur T., *Wilmington, Del.*
Griffeth, Donald G., *No. Plainfield, N. J.*
Hall, Herbert S., *Camden, N. J.*
Harris, Henry C., *Lawrence, Kan.*
Harris, Norman R., *Grand Island, N. Y.*
Haven, Allan M., *Texas City, Tex.*
Herbst, Adolph, *New York, N. Y.*
Husband, W. H. W., *Niagara Falls, Ont., Canada*
Kaigler, Jack J., *Richland, Wash.*
Kelly, Thomas F., *Midland, Mich.*
Kimberling, William R., *So. Charleston, W. Va.*
Kluck, Dale, *Saginaw, Mich.*
Koble, Robert A., *Morgantown, W. Va.*
Lange, M. D., *Cuyahoga Falls, Ohio*
Leigh, Marjorie W., *Short Hills, N. J.*
Leuchak, Walter P., *Chester Springs, Pa.*

TECHNICAL TOPICS

WELDING STAINLESS ALLOYS

Norman S. Mott
Chief Chemist and Metallurgist
The Cooper Alloy Foundry Co.

In the welding of stainless alloys, four types of composition have to be taken into consideration—the hardenable martensitic straight chromium group; the non-hardenable ferritic straight chromium group; the corrosion resisting chromium-nickel group, and the heat resisting chromium-nickel group. These alloy compositions have, in varying degrees, greater thermal expansion and lower thermal conductivity than carbon steels, and in some instances have carbide mannerisms which affect corrosion resistance.

When the torch flame or arc is applied, the metal is heated to a very high temperature only in the area being welded. The heated metal expands and tends to push out in various directions against the colder surrounding metal, producing severe internal stresses. When the heat source is removed, the resultant contraction produces pulling stresses acting between the cooling and the cold metal. If the metal does not have sufficient ductility to stretch and accommodate itself to these great stresses, cracking will result. This is most prevalent in the lower ductility straight chromium grades. By making temperature gradients as gradual as possible, this danger can be minimized.

In the chromium-nickel corrosion resisting alloy types, a form of grain boundary carbide precipitation occurs during welding. To offset the dangers of intergranular corrosion, these carbides must be put into solution by subsequent heat treatment before the welded metal is put into use.

Difficulties which are involved in welding cast stainless steel can be overcome through the use of prewelding and post-welding thermal treatments as indicated below. Alloys for heat resistance applications usually do not require any thermal treatment after welding.

Alloy	REMARKS
5%Cr	Preheat to 400° F. or over. After welding, cool to not less than 300° F. then heat to 1650° F. . . . hold for 1 hour, furnace cool to 1350° F., hold for 2 hours, then air cool.
9%Cr	Preheat to 400° F. or over. After welding, cool to not less than 300° F. then heat to 1350° F. . . . hold for 2 hours, then air cool.
12%Cr	Preheat to 400° F. or over. After welding, cool to not less than 300° F. then heat to 1350° F. . . . hold for 4 hours, then air cool.
16%Cr	Preheat to 250 - 300° F. After welding, cool to 250° F. or lower, then heat to 1450° F. . . . hold for 4 hours, then air cool.
18%Cr	Preheat to 250-300° F. After welding, cool to 150° F. or lower, then heat to 1450° F. . . . hold for 4 hours, then air cool.
27%Cr	Preheat to 250° F. or over. After welding, heat to 1650° F. . . . hold for 2 hours, then rapidly air cool. If distortion is feared stress-relieve weld for 1 hour at 1350° F. followed by air cooling.
18-8S	Preheat not required. After welding heat at 2000° F. for 1 hour, then water quench.
18-8SCb	Preheat not required, nor is post heat. However, after welding, it may be stress-relieved at 1650° F. for 2 hours followed by air cooling.
18-8SMo	Preheat not required. After welding heat at 2000° F. for 1 hour, then water quench. Sufficiently ferritic alloys can often be used without post heating.
FA-20	Preheat to 400° F. After welding cool very slowly then heat to 2000° F. . . . hold for 1 hour and water quench.

Copies of this article reprinted on heavy stock for convenient filing are available on request.

The **COOPER ALLOY** Foundry Co. Hillside, N. J.

LOCAL SECTION

WESTERN MASSACHUSETTS

At the annual December business meeting, held Dec. 13, 1951, at Blake's Restaurant in Springfield, Mass., the following officers for 1952 were elected:

Chairman	H. L. Minckler
Chairman-elect	A. W. Low
Treasurer	W. K. Fitch
Secretary	D. V. Bierwert
Exec. Committee	E. O. Ohsol

Before the business meeting, Otis Pronovost, investment broker of Springfield, led a discussion on "The Behavior of Chemical Companies in the Stock Market."

Reported by R. H. Marks

EL DORADO

At the final meeting for 1951, held at Dewey's Steak House in El Dorado, Ark., 100 members and guests were present. The guest speaker was R. C. Bennett of Commercial Solvents who talked on "The manufacture and uses of penicillin." After a brief history of the development of penicillin, the present manufacturing methods were described.

The following officers for the year 1952 were announced:

Chairman	A. A. Feerick
Vice-Chairman	K. I. Glass
Secretary-Treasurer	O. A. Fuchs

Reported by R. L. Alexander

SOUTH TEXAS

Recently elected officers are as follows:

Chairman—C. L. Dickinson, Kolker Chemical Works, Houston
Chairman - elect—W. B. Franklin, Humble Oil & Refining Co., Baytown
Secretary—W. R. Trutna, Du Pont Co., LaPorte
Treasurer—W. L. Bolles, Gulf Publishing Co., Houston
Executive Committee—M. C. Hopkins, Pan American Refining Co., Texas City; J. J. McKetta, University of Texas, Austin; H. D. Foster, Du Pont Co., LaPorte. The Executive Committee consists of the elected members, plus the other elected officers of the Section and W. E. Alexander, the past chairman.

Reported by W. E. Alexander

EAST TENNESSEE

The 31st general meeting was held in the Foremen's Room, Tennessee Eastman Co., Kingsport, Tenn., Dec. 10, 1951.

Officers for 1952 are:

Chairman	T. W. Doub
Vice-Chairman	E. L. Gustafson
Secretary-Treasurer	Ben Thompson
Director	R. C. Burton

Reported by J. K. Pannill

SECRETARY'S REPORT

S. L. TYLER

THE Executive Committee met at the Offices of the Institute Jan. 4 and the matters to come before it were largely of a routine nature consisting of approval of bills and similar items.

With one exception those whose names appeared in the December issue of "C.E.P." were elected to the grades of membership as indicated. There were also 328 elected to Student membership.

Several additions were made to committee personnel upon the recommendation of committee chairmen.

Two elections were rescinded because of non-acceptance.

The names of the following members were placed on the Suspense List because of having entered the Armed Services: E. A. Brown, C. G. Lester, J. F. Magness, R. H. Meyer, Jr., E. W. Samoden, J. H. Staib and M. A. Vogel. It was reported that A. J. Wilson had been discharged from the Service and has now returned to civilian life.

Thirty resignations had been received and were accepted. Reasons for resignation were invariably that the member's work was no longer in the chemical engineering field.

The Council held an active and important meeting at The Chemists' Club Jan. 4. After approval of Minutes of the previous meeting a considerable portion of the morning session of the meeting was devoted to a detailed review of the by-laws as prepared by the Constitution and By-Laws Committee and it was voted to approve these by-laws with a few minor modifications with which the Executive Committee was charged.

In accordance with practice members of Council were appointed as liaison members of Council to represent the various standing committees of the Institute. All committee chairmen have been advised of their representatives on Council.

The Council recognized the passing during 1951 of A. E. Marshall and James G. Vail, former Presidents of the Institute and Resolutions of regret were passed and sent to the families of the deceased.

H. D. Wilde was appointed representative with L. P. Whorton as alternate on the American Standards Association Committee Z59 on Fluid Permeation.

In accordance with the rules of the Perkin Medal Committee, T. H. Chilton, W. I. Burt and W. T. Nichols will be our official members of the Perkin Medal Committee. D. B. Keyes, W. L. McCabe and F. J. Van Antwerpen were appointed as alternates to the regular members.

The 1952 Committee on Committees which is a special committee of Council was appointed as follows: W. T. Nichols, chairman, G. E. Holbrook and C. G. Kirkbride.

PROFESSIONAL LEGISLATION COMM. REPORTS

A report of the A.I.Ch.E. Committee on Professional Legislation has been received from John M. Weiss, chairman. In his statement Mr. Weiss said that a number of amendments to license laws were enacted over the past year in a number of states. With one exception all were designed to bring the law more closely in accord with the Model Registration Law. The one exception, Mr. Weiss reports, is New Hampshire which made registration mandatory instead of permissive as heretofore.

Mr. Weiss also stated that 167,414 engineers were registered in the United States and territories but that 68% were in ten states, as follows:

California	24,439
New York	17,416
Illinois	16,109
Ohio	15,485
Pennsylvania	12,891
Texas	7,752
Massachusetts	5,425
New Jersey	5,321
Missouri	4,951
Indiana	4,409
	114,198

EXTRA COMPENSATION FOR ENGINEERS

A general letter was issued recently by the Salary Stabilization Board dealing with additional compensation for professional engineers who are required regularly to work hours in excess of those contemplated in determining their current salaries. The order of the board states that where such a practice existed on Jan. 25, 1951, the board permits continuance of the practice, and that in the absence of any such precedent, a professional engineer employed in a professional capacity may receive additional compensation up to his straight-time rate for an extended work-week without the approval of the Office of Salary Stabilization.

The General Salary Order No. 8 titled, "Regularly Extended Work-Week for Professional Engineers," defines a professional engineer as ". . . a person employed in a professional capacity, who, by reason of his special knowledge of the mathematical and physical sciences and the principles and methods of engineering analysis and design, acquired by professional education and practical experience, is qualified to practice engineering."

CANDIDATES FOR MEMBERSHIP

Leyse, R. H., *Richland, Wash.*

Linak, James C., *So. Charleston, W. Va.*

Madden, William W., *Pottstown, Pa.*

Martin, Bernard L., *Wilmington, Del.*

Mazanek, John B., *Fort Edward, N. Y.*

McHarg, Robert E., *Tulsa, Okla.*

McNally, C. L., *Woodside, N. Y.*

McNulty, Herbert W., Jr., *Jamaica, N. Y.*

Merdler, Louis, *Midland, Mich.*

Mixisin, Andrew P., *Texas City, Tex.*

Morrow, Brian J., *Roselle, N. J.*

Mourich, Frank L., *Kennewick, Wash.*

Nilsen, Per Hallvard, *Lillestrom, Norway*

Novak, Edwin Martin, *New York, N. Y.*

Oldenburg, Charles C., *New York, N. Y.*

Orazem, Gerald J., *Wilmington, Del.*

Oxenham, Alfred J., *Pittsburgh, Pa.*

Parsons, Donald S., *Towanda, Pa.*

Polle, Charles R., Jr., *Burlington, Iowa*

Rehmus, Frederick H., *Philadelphia, Pa.*

Roney, John L., *Antioch, Calif.*

Rusin, Daniel, *Chicago, Ill.*

Ryan, John D., *Charleston, W. Va.*

Selldorff, John T., *Oak Ridge, Tenn.*

Sheeks, Eddie V., III, *Boulder City, Nev.*

Snell, Ray W., *Rockville, Ind.*

Stack, Robert L., *Texas City, Tex.*

Strack, William J., *Midland, Mich.*

Sutton, Carl, *Brownsville, Tex.*

Szabo, Ted T., *Lawrence, Kan.*

Taffee, W. F., Jr., *Nitro, W. Va.*

Taggart, Ross A., *Chattanooga, Tenn.*

Tefft, Thomas H., *Midland, Mich.*

Umberger, John C., *Kingsport, Tenn.*

Unangst, H. B., *Metuchen, N. J.*

Vincent, George C., *Terre Haute, Ind.*

Vitale, D. Nicholas, *Baden, Pa.*

Von Halle, Edward, *Oak Ridge, Tenn.*

Wilcox, Allan C., *Midland, Mich.*

Zahn, Harvey F., *Lawrence, Kan.*

LOCAL SECTION NEWS

MARYLAND

This Section held its annual business meeting Dec. 11, 1951, at The Johns Hopkins University. Officers elected for the coming year were:

Chairman . . . . F. C. Dehler
Vice-Chairman . . . . L. J. Trostel
Secretary-Treasurer . . . . . L. C. Palmer

A discussion took place on the report of the President's Water Resources Policy Commission, led by E. W. Guernsey.

The meeting was concluded by a showing of the Freeport Sulfur Co.'s film, "Yellow Magic."

Reported by Alan Beerbower

CHICAGO

Approximately 120 members and guests met at the Western Society of Engineers' suite Jan. 16 for dinner and heard a talk, "Fluidization—A New Operating Tool," given by C. J. Wall, engineer, Dorr Co.'s fluosolids division at Stamford, Conn.

Mr. Wall described fluidization as a new unit process with varied applications other than its widely known use in petroleum catalytic cracking.

Henry F. Notting, Standard Oil Co. (Ind.) and Herschel Stewart, Victor Chemical Corp., presented a 12-minute broadcast describing the vocational guidance activities of the Public Relations Committee of this Section. It was given over WMAQ at 11:00 A.M., Saturday, Jan. 12.

The event was directed by Elizabeth Hart, of the National Broadcasting Co., who organized the program, which was of an informal question-and-answer type. A definition of engineering was provided, and the qualities desired in an engineer were all well presented.

Reported by Thorpe Dresser and Thomas A. Matthews II

WESTERN NEW YORK

Kermit Fischer, president of Fischer & Porter Co., spoke at the Jan. 10 dinner meeting on the future of private enterprise in the United States. It was his opinion that a sociological change will be required in this country in which industry accepts more of the responsibility for employees' welfare and security. Engineers, as a class, tend to be lacking in humanism and tend to regard people more as machines, he said.

Reported by W. C. Greenwald

Mr. Insulation says:

"Start out with the right materials properly applied...and dividends from your insulation investment will be never ending."
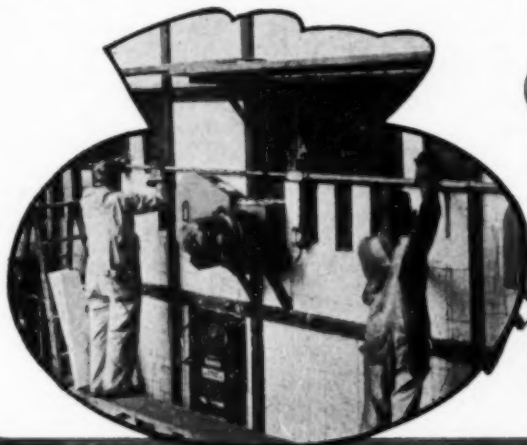
Here are two important reasons why it will pay you to let Johns-Manville serve as your insulation headquarters:

YOU GET THE RIGHT MATERIALS — Regardless of the service conditions on your job, Johns-Manville has an insulation that fits the need. That's because Johns-Manville manufactures a wide variety of insulations of asbestos and other selected raw materials—for service from 400F below zero to 3000F above. Johns-Manville offers this complete line because industry requires many types of insulations and because no one material can properly serve as a jack-of-all trades for use on all jobs.

YOU GET THE RIGHT APPLICATION — Insulations serve at top efficiency only when properly applied. J-M Insulation Contract Firms have men with generations of insulation experience and training in Johns-Manville application methods. The way they engineer your job is your assurance that your insulation investment will pay a high return through the years.

Why not call on insulation headquarters for engineering advice about your insulation work. J-M Insulation Engineers are available to help select the *right* insulation for your particular service conditions. Write Johns-Manville, Box 290, New York 16, N.Y.

Johns-Manville *first in* INSULATIONS

LOCAL SECTION NEWS

(Continued from page 58)

SOUTHERN CALIFORNIA

At the Jan. 15 meeting held at the Rio Hondo Golf Club, Carlos Wood, chief preliminary design engineer for Douglas Aircraft Co., addressed the group on "Characteristics and Cost Considerations of Turbine Aircraft Engine Fuels."

The February meeting will take place at Scully's Cafe on Crenshaw Boulevard in Los Angeles where Lynn A. Blackmun, technical director, West End (Calif.) Chemical Co,. will discuss the operations at the Searles Lake plant of the West End Chemical Co. where limestone, coke and Searles Lake brine are processed to produce various grades of soda ash and borax.

The officers of this Section for 1952 are as follows:

Chairman—F. J. Lockhart, Univ. So. Calif.
Vice-Chairman—G. R. Lake, Union Oil Co.
Secretary-Treasurer—A. K. Brumbaugh, General Petroleum Co.
Executive Comm.—Senior Member, E. R. McCartney, Fluor Corp., Ltd.; Junior Member, P. G. Young, Ralph M. Parsons
Representatives to Los Angeles Eng. Council of Founder Societies—F. C. Brunner, C. F. Braun & Co.

Newly Appointed Program Chairman —D. R. Stern, Western Electrochemical Co.

The names listed in the December, 1951, "C.E.P." on page 54 were nominees and not, as stated, new officers.

Reported by Gale S. Peterson

ST. LOUIS

The Jan. 15 meeting of this Section held at the York Hotel featured a talk by G. C. Thrift on "The Development of the Koch Tray." He reviewed the development of the Kaskade tray and the Venturi tray.

The meeting was attended by 95 members, student members and guests.

At a meeting held late in 1951 S. A. Laurich, assistant manager of the crystallizer department of Struthers Wells Corp., spoke on "Industrial Crystallization."

Officers of this Section for this year are:

Chairman—C. P. Orr, Monsanto Chemical Co.
Vice-Chairman—D. E. Morris, Mallinckrodt Chemical Works
Secretary-Treasurer—D. F. Chamberlain, Washington University

Reported by D. S. Weddell
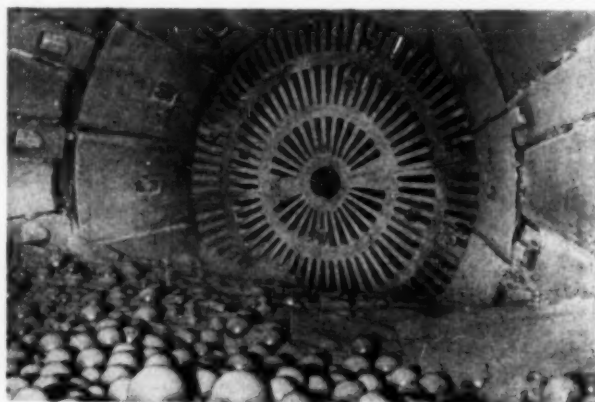
Dependability

GLC Anodes for the electrolytic industry are dependable —

they stand the test of comparison.
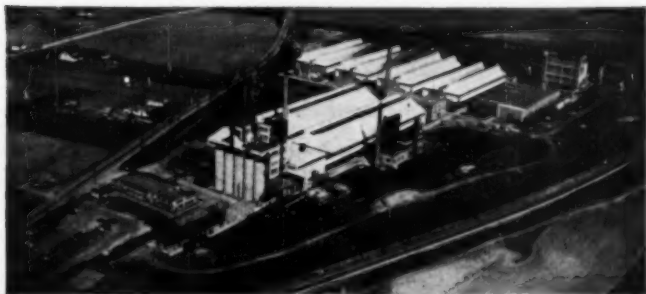
Air View—
Morganton,
N. C., Plant

LOCAL SECTION NEWS
(*Continued from page 60*)

OHIO VALLEY

A meeting was held Jan. 7 at the Engineering Society Building in Cincinnati. J. H. Rushton, director, department of chemical engineering, Illinois Institute of Technology, talked on mixing.

A dinner was held by this section Feb. 4 at which Richard Ballman and W. H. Williamson talked on "Chemical Plant Hazards and Safety Standards."

Reported by N. W. Morley

CHARLESTON, W. VA.

The Charleston Section of A.I.Ch.E. records with sorrow the passing on Jan. 9, 1952, of one of its most distinguished members, Irvin L. Murray. He was one of the founders of the Section and served as its chairman in 1941. Mr. Murray was devoted to the affairs of the Institute, serving on many committees and being the first member from this Section to be elected a Director (1949-51). His good taste and decisive judgment were instrumental in shaping the course of this Section, and will long be remembered by all who knew him.

Born in New York on May 11, 1904, he received a B.S. from the City College of New York in 1924 and a M.S. from M.I.T. in 1926. He became associated with Carbide and Carbon Chemicals Co., South Charleston, W. Va., in 1927 and held the position of director of engineering at the time of his death. (See also page 72.)

NEW YORK

Logan B. Emlet of Carbide and Carbon Chemicals Co., who is executive director of Oak Ridge National Laboratory, addressed this Section Jan. 23 on "Industrial Uses of Atomic Energy." Mr. Emlet discussed some services already being performed at Oak Ridge for industry, including production of isotopes and irradiation of industrial samples. He described "activation analysis," a procedure in which a sample containing unidentified elements is irradiated in the reactor and then analyzed by identifying the specific radiation characteristics of the isotopes produced. He also covered the potential industrial uses of atomic energy.

The search for suitable materials for jacketing the fuel element in reactors, Mr. Emlet said, has led to efforts to produce larger quantities of purified zirconium. This metal is not only heat- and corrosion-resistant but also has low affinity for neutrons.

Reported by C. H. Chilton

LOCAL SECTION NEWS

PHILADELPHIA-WILMINGTON

The third meeting of the 1951-52 season was held at the Du Pont Country Club, Wilmington, Del., Jan. 8, 1952. About 104 persons were present for dinner and about 215 members and guests attended the meeting that followed.

Henry Evans of the Delaware Power and Light Co., spoke briefly on "Delaware Engineering Association."

The main speaker of the evening was F. T. McClure, chairman of the research center of the Applied Physics Laboratory of John Hopkins University, whose subject was "Recent Progress on Guided Missiles."

Reported by W. E. Osborn

KNOXVILLE-OAK RIDGE

The following have been elected officers of this Section for 1952:

Chairman—W. B. Harrison, III, Oak Ridge National Lab.
Vice-Chairman—W. B. Allred, AEC-Oak Ridge Office
Secretary—S. H. Jury, Univ. of Tenn.
Treasurer—J. O. Davis, Oak Ridge National Lab.
Director—F. L. Steahly, Director, Chemical Tech. Div., Oak Ridge National Lab.
Director—L. C. Peery, Liaison Officer, Oak Ridge National Lab.
Director (Past-Chairman) — A. C. Jealous, Oak Ridge National Lab.

R. W. McNamee, superintendent, research and development, Carbide and Carbon Chemicals Co., South Charleston, W. Va., addressed the annual banquet meeting in Oak Ridge, Jan. 15, on the topic, "Research with a Purpose."

Reported by A. Carleton Jealous

PITTSBURGH

An audience of 175 members and guests of this Section heard a first-hand report on a new low-temperature carbonization process in an illustrated talk by V. F. Parry, of the U. S. Bureau of Mines. The occasion was the Junior Members' night held Jan. 9 at the Royal York Apartments and sponsored by a junior committee headed by R. E. Ryan, Koppers Co.

Mr. Parry, chief of the coal branch at the Bureau's laboratories at Denver, Col., pointed out that about two thirds of the known coal reserves of this country are located in the Western states and that these reserves consist largely of lignite and other low rank coals of either noncoking or weakly coking types.

Reported by Hugh L. Kellner

PEOPLE

Clayton F. Ruebensaal, formerly technical director of the plastics and resins department, has been named to the newly created position of commercial development manager of the United States Rubber Co.'s chemical division at Naugatuck, Conn. Mr. Ruebensaal, who received his B.S. in chemical engineering from Case Institute of Technology, joined Naugatuck Chemical in 1949 when the company purchased the assets of the Glenn L. Martin Co.'s chemical division, which he had helped to organize.

J. Strother Miller, previously with the Barber Asphalt Corp., but since retirement is now with Miller-Warden Associates, has changed his address from P. O. Box 415, Rahway, N. J., to 391 Elm Avenue, Rahway. There he continues as consultant in asphalt technology and related engineering problems.

Thomas M. O'Grady, formerly a graduate student in the chemical engineering department of the University of Notre Dame, is now a research chemical engineer at the Wyandotte Chemicals Corp., Wyandotte, Mich.

Jesse Werner, formerly assistant manager of the process development department at the General Aniline & Film Corp.'s plant at Grasselli, N. J., has been appointed technical assistant to the vice-president of operations, General Aniline Works Division. In this new capacity, Dr. Werner will assist in programming research, market research and development.

James S. Bruce, a division supervisor since 1944, has been appointed assistant superintendent of the Eastman Kodak Co.'s paper service division at Rochester, N. Y. After working summers for Kodak since 1937, Mr. Bruce joined the company full time in 1939 as a chemical engineer in the Kodak Park paper service division.

Daniel B. Curll, Jr., has become associated with Lee Higginson Corp., New York, as an adviser on projects in the chemical engineering and related fields. He was formerly assistant to the vice-president in charge of sales at the Commercial Solvents Corp., N. Y., and previously assistant to the president of the Rumford Chemical Works, Rumford, R. I.

PEOPLE

H. B. Coats, who has been with the Blaw-Knox Co. since 1943, has been made director of the company's newly organized research and development department at Pittsburgh, Pa. Dr. Coats, who received his doctorate in chemical engineering at the University of Michigan, was previously affiliated with the Leslie Laboratories at Ann Arbor and with the Upjohn Co. of Kalamazoo.

H. D. Radford has been promoted to head the process development section, and **John A. Ridgway** has been appointed research associate in the research and development department of Pan American Refining Corp., Texas City, Tex. Dr. Radford, who received his Ph.D. from the University of Missouri, was formerly a group leader in the research and development department. Mr. Ridgway, who holds an M.S. from the University of Minnesota, was formerly section head of the research laboratory.

Lowell L. Fellinger has been appointed assistant director of engineering for the Monsanto Chemical Co.'s organic chemicals division and **Jean R. Okel** will replace him as the division's coordinator of technical personnel procurement. Mr. Fellinger, who received his Sc.D. from M.I.T., joined the company in 1941 as a research chemist. Mr. Okel, who received his B.S. in chemical engineering from Washington University, was formerly assistant to the executive vice-president.

William Hirschkind has been appointed technical adviser to Leland I. Doan, president of The Dow Chemical Co., Midland, Mich., and **Robert G. Heitz** has been named to replace him. Dr. Hirschkind has been research director for the company's Great Western division, Pittsburg, Calif. Mr. Heitz has been associated with Dow since his graduation from California Institute of Technology in 1936.

J. S. Moczek, formerly a project engineer in the development group of the company's John F. Queeny plant, has been made senior technologist in the Monsanto Chemical Co.'s general engineering department. Mr. Moczek, who received his B.S. in chemical engineering from the University of Michigan, was previously with the Barrett division of Allied Chemical & Dye Corp., Philadelphia, Pa.

John J. Hickerson, development engineer, U. S. Radium Corp., New York, from 1943-51, has been appointed a research chemical engineer in the chemistry and chemical engineering research department at Armour Research Foundation of Illinois Institute of Technology. Mr. Hickerson received his bachelor's degree in chemical engineering from the University of Missouri in 1943. He served in the Navy two years as an electronics mate.

August H. Pritzlaff, formerly an industrial consultant, has joined the research staff of Standard Oil Co. (Ind.), Whiting, Ind. Mr. Pritzlaff, who received his B.S. degree at Northwestern University, is studying for his Ph.D. in chemical engineering.

David L. Eynon, Jr., assistant general manager of the organic chemicals division, Monsanto Chemical Co., St. Louis, Mo., has been granted a leave of absence to attend the Advanced Management Program at Harvard University Graduate School of Business Administration. Mr. Eynon joined Monsanto's Merrimac division research department at Everett, Mass., in 1933. He has been a member of the organic division management since 1945 when he was appointed assistant to the general manager. He also enrolled in the 13-week program at Harvard in 1950.

Fred W. Arndt has been appointed eastern representative with headquarters in New York, for the Heil Process Equipment Corp. Mr. Arndt, who received his M.S. from Stevens Institute of Technology, has had several years' experience as engineer and sales engineer in the process equipment field. He was previously sales engineer for the Turbo-Mixer Corp., New York.

FOXES IDENTIFIED

It was erroneously stated in the January issue, page 60, that Joseph M. Fox, the 3rd, had been associated with Sharp & Dohme, Inc., and is now with the M. W. Kellogg Co., Glen Ridge, N. J. Joseph M. Fox, the 3rd, has been associated with Kellogg since 1947 and is research chemical engineer in the Jersey City plant. He was never affiliated with Sharp & Dohme. Joseph Milton Fox still holds the position of waste control engineer with Sharp & Dohme, Inc., Philadelphia, Pa. The similarity in names caused the error.

Chalmer G. Kirkbride has been advanced from vice-president of research and development to president of Houdry Process Corp., Phila., Pa. Mr. Kirkbride was the winner of the 1951 Professional Progress Award in Chemical Engineering. Prior to going to Houdry in 1946, he had been associated with the Standard Oil Co. of Indiana, Pan American Refining Corp., and the Magnolia Petroleum Co. Mr. Kirkbride, who received his M.S. from the University of Michigan, has been active on A.I.Ch.E. committees and at present is a Director with a term expiring in 1952. **Claude C. Peavy**, vice-president in charge of engineering and sales since 1948, has been elected vice-chairman of the Board. Dr. Peavy, who received his Sc.D. from the University of Michigan, joined Houdry in 1946 and a year later was appointed chief engineer. Previously, he had been with E. B. Badger & Son and with the Socony-Vacuum Oil Co.

MEES, FORTY YEARS WITH EASTMAN KODAK

C. E. Kenneth Mees, vice-president in charge of research for Eastman Kodak Co., completed 40 years of service with the company in January. Dr. Mees studied in his native England and then joined the firm of Wratten and Wainwright there. He came to the U. S. in 1912 and shortly organized and directed a research laboratory for Kodak.

During World War 1 Dr. Mees established the first school of aerial photography at Kodak Park, and in 1918 added a department of synthetic organic chemistry to Kodak research laboratories. In 1923 he went to Kodak limited in London where he served for about a year as European acting manager. Subsequently he became a director of Kodak and was elected a vice-president in 1934.

Eugene Miller recently became a chemical engineer in the Ordnance Corps., Redstone Arsenal, Huntsville, Ala. He was formerly a process engineer in the special projects department of M. W. Kellogg Co., Jersey City, N. J.

PEOPLE

Irving Hochstadter, consulting chemical engineer, New York, has been retained by W. W. Slocum & Co., engineers of Newark, N. J. Dr. Hochstadter will advise the company on chemical economics, plant surveys, processing techniques, and plant construction.

Finley C. Nicholson has been appointed to the newly created post of manager of operations of The Davison Chemical Corp., Baltimore, Md. Mr. Nicholson, a graduate of Purdue in chemical engineering, has been with Davison in various capacities since 1942; his most recent position was that of manager of the Cincinnati catalyst plant.

Ralph N. Lulek was recently elected vice-president of St. Maurice Chemicals Limited and a member of the St. Maurice board of directors. He is also vice-president and director of Heyden Chemical Corp., and a member of the Heyden Management Committee. Dr. Lulek received his Ph.D. from the University of Graz, Austria. Early in his career in this country he was plant manager for the Publicker Commercial Alcohol Co., Philadelphia, Pa., and later became research manager for the Heyden Chemical Corp., where he advanced to the position of vice-president and director. °

David S. Bruce, formerly assistant plant manager, Hercules Powder Co., Parlin, N. J., is now manager, new products production cellulose products department of the company at Wilmington, Del. Mr. Bruce will work with the development group in planning full-scale processes and plants for new products. He will also assist the management of the department on other operating problems.

PEOPLE

Charles L. Thomas has been ap-
pointed to the research and development
staff of the Sun Oil
Co., Philadelphia,
Pa. Dr. Thomas
received his B.S.
and M.S. from the
University of North
Carolina and a
Ph.D. from North-
western University.
He has been di-
rector of research
and development
for the Great Lakes Carbon Corp., the
past six years. For a considerable per-
iod he was associated with Universal Oil
Products Co.

A. O. Zoss and **Clyde McKinley**
have received new administrative ap-
pointments at General Aniline & Film
Co.'s Grasselli, N. J., plant. Dr. Zoss,
heretofore superintendent of the special
products division, has been made plant
production manager and Dr. McKinley,
formerly chemical engineering assistant
to the division's manager, succeeds Dr.
Zoss in his former capacity. Dr. Zoss,
who received his Ph.D. from the Uni-
versity of Notre Dame, has been with
the company since 1941. Dr. McKinley,
who received his Sc.D. from the Uni-
versity of Michigan, joined General Ani-
line in 1943.

Marshall Sittig, technical writer, has
joined the information division of the
research laboratories of Ethyl Corp., De-
troit, Mich. Mr. Sittig, who holds a
B.S. degree from Purdue University,
was formerly with the Chrysler Corp.,
Detroit, Mich.

Donald B. Keyes has been engaged
by Arthur D. Little, Inc., industrial re-
search and engi-
neering organiza-
tion of Cambridge,
Mass., as special
consultant. Dr.
Keyes, a member
of the board of
directors of the
Heyden Chemical
Corp., is adviser to
the National Asso-
ciation of Manu-
facturers Research Committee in the
field of research administration.

The holder of degrees from various
universities, Dr. Keyes has been direc-
tor of research and development for
U. S. Industrial Alcohol and U. S. In-
dustrial Chemical Companies, head of
the chemical engineering division of the
University of Illinois, and a vice-presi-
dent of Heyden Chemical Corp.

CLASSIFIED SECTION

SITUATIONS OPEN

Necrology

I. L. MURRAY

Irvin L. Murray, director of engineering for the Carbide & Carbon Chemicals Co., who contributed much to the engineering and design of many major chemical plants and processes of his company during the past 25 years, died Jan. 9, 1952. He had been associated with Carbide throughout his professional career, beginning in 1927 after a year spent as research assistant in the research laboratory at M.I.T. First in charge of operation of a unit chemical plant he later became chief process engineer and subsequently director of engineering. During 1942 and 1943 he was a member of the American Rubber Mission to the Soviet Union. Mr. Murray received a B.S. from City College of New York in 1924 and an M.S. from M.I.T. in 1926. He had an active interest in the affairs of the Institute, and served as a Director during 1949-51. (See also page 62.)

R. E. MONTONNA

Ralph E. Montonna, director of the engineering experiment station at the University of Minnesota, died Jan. 7. Professor Montonna, who was a graduate of Syracuse University and received his Ph.D. degree at Yale, went to University of Minnesota in 1924. He has been on the staff ever since, except from 1946-50 when he was director of engineering research at Syracuse University, New York. Previously, he had been with the Solvay Process Co., Syracuse, the U. S. Color and Chemical Co., Ashland, Mass.

DEANE BURNS

Deane Burns, personnel manager of the Harshaw Chemical Co., Cleveland, Ohio, died Jan. 24, 1952. Mr. Burns received his B.S. in chemical engineering from the University of Illinois in 1907 and joined the Corn Products Refining Co.'s (Ill.) plant. In 1910, he became affiliated with the National Carbon Co., Cleveland, Ohio.

H. P. BANKS

Harry Pickands Banks, vice-president and general manager of the Monsanto Chemical Co.'s Western division, died Dec. 26, 1951. Mr. Banks, who received his B.S. degree in chemical engineering from the University of Michigan, had been with Monsanto since 1948. Previously, he had been affiliated for a number of years with I. F. Laucks, Inc., Seattle, Wash.

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